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**Wu et al.**

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(54) **METHOD, APPARATUS, AND SYSTEM FOR WIRELESS MATERIAL SENSING**

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(51) **Int. Cl.**  
**G01N 22/00** (2006.01)  
**G01S 7/41** (2006.01)

(Continued)

(52) **U.S. Cl.**  
CPC ..... **G01N 22/00** (2013.01); **G01S 7/411** (2013.01); **G01S 13/88** (2013.01)

(58) **Field of Classification Search**  
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(Continued)

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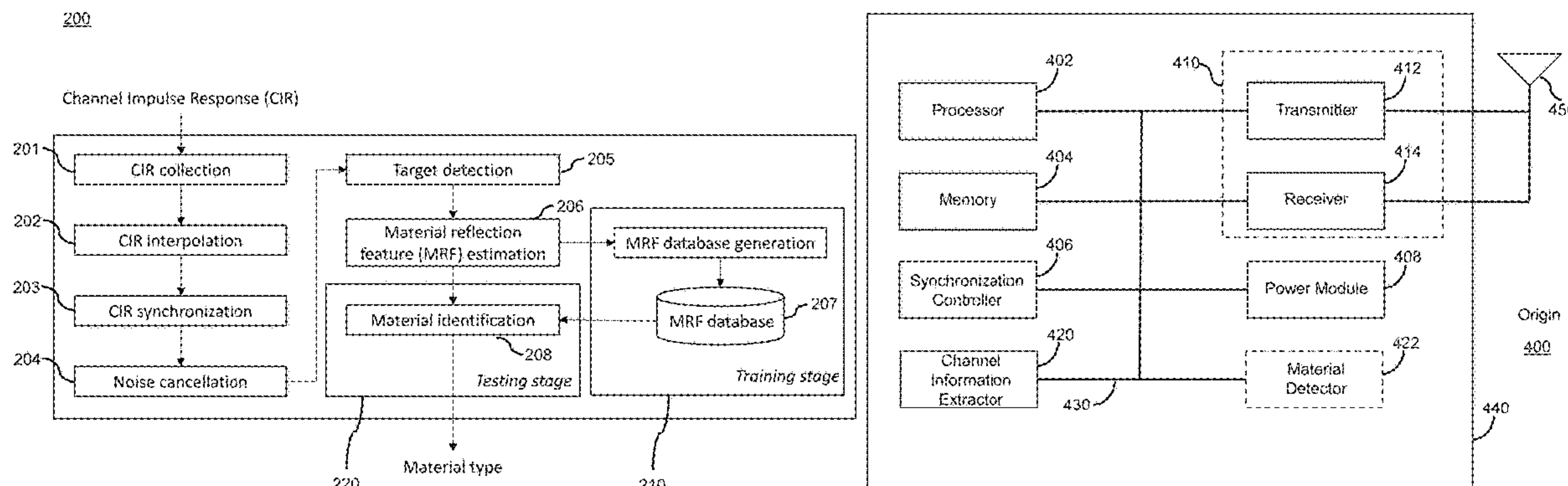
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*Primary Examiner* — Bernarr E Gregory

(57) **ABSTRACT**

Methods, apparatus and systems for wireless material sensing are described. In one example, a described system comprises: a transmitter configured for transmitting, using transmit antennas, a first wireless signal through a wireless multipath channel of a venue; a receiver configured for receiving, using receive antennas, a second wireless signal through the wireless multipath channel; and a processor. The second wireless signal comprises a reflection or a refraction of the first wireless signal at a surface of a target material of an object in the venue. The processor is configured for: obtaining a plurality of channel information (CI) of the wireless multipath channel based on the second wireless signal, wherein each CI is associated with a respective transmit antenna and a respective receive antenna; computing a material analytics based on the plurality of CI; and determining a type of the target material of the object based on the material analytics.

**30 Claims, 23 Drawing Sheets**



- (51) **Int. Cl.**  
*G01S 13/88* (2006.01)  
*G01S 13/00* (2006.01)

- (58) **Field of Classification Search**  
USPC ..... 342/22; 324/637-639, 642  
See application file for complete search history.

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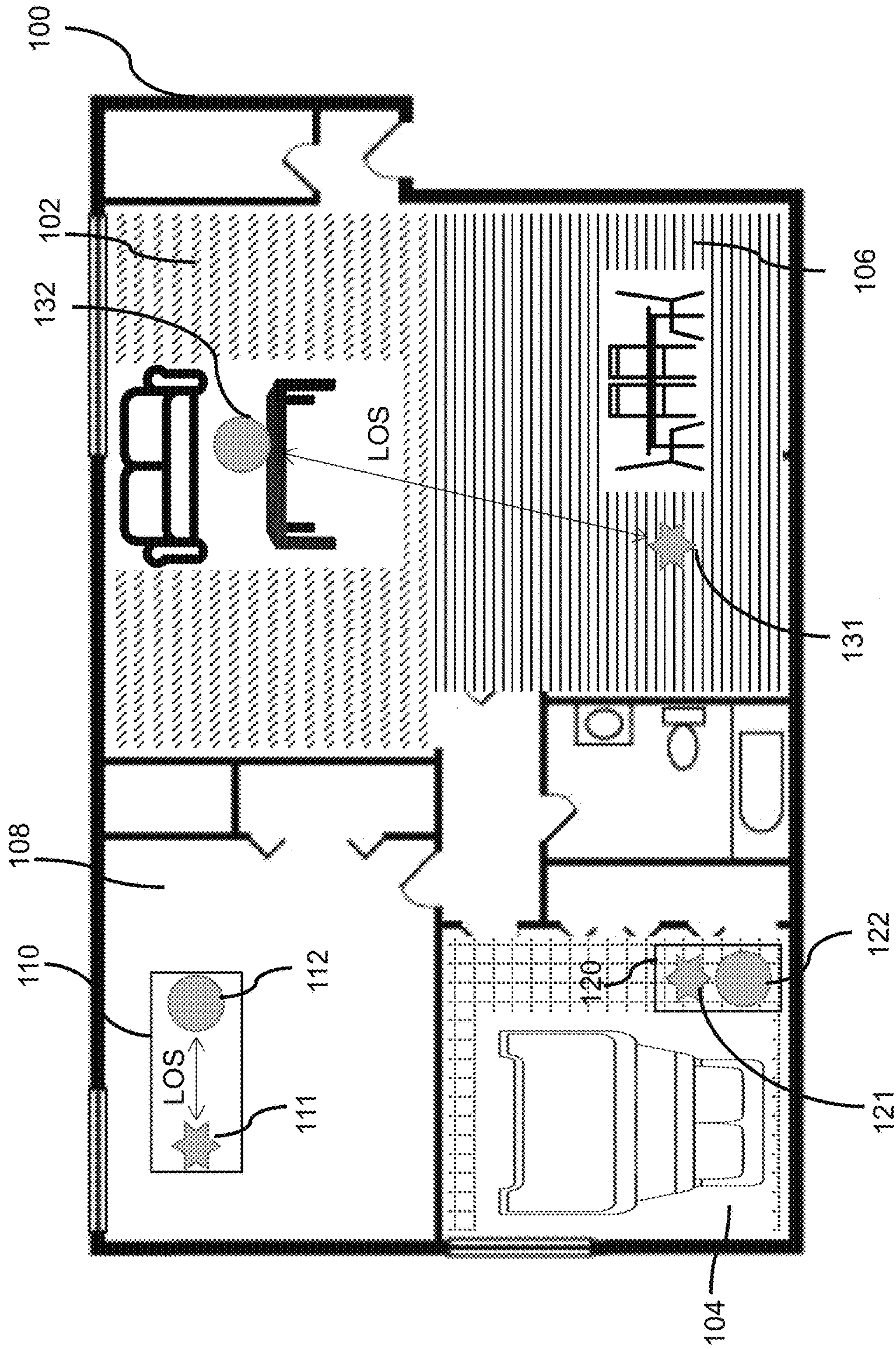


FIG. 1A



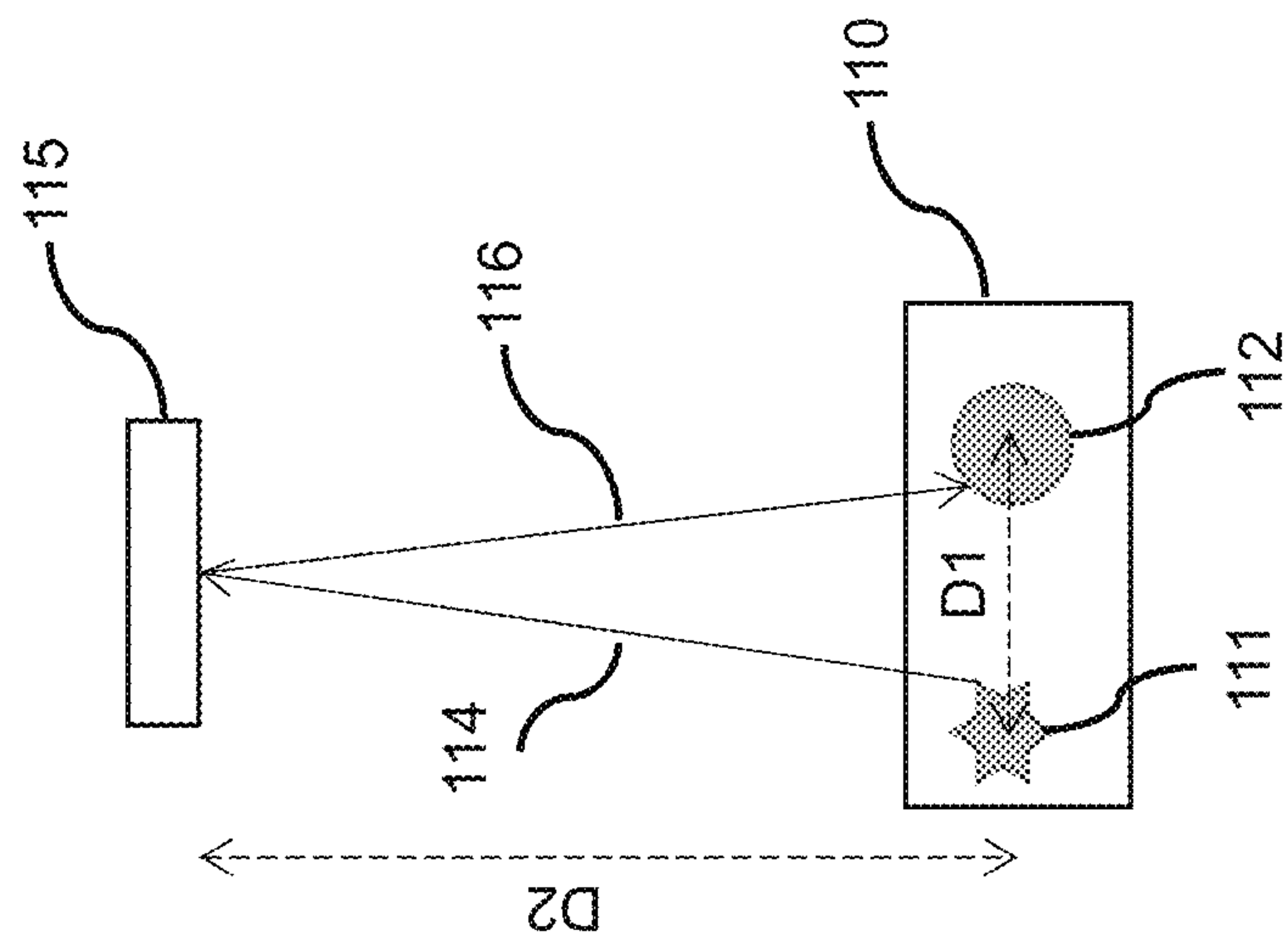
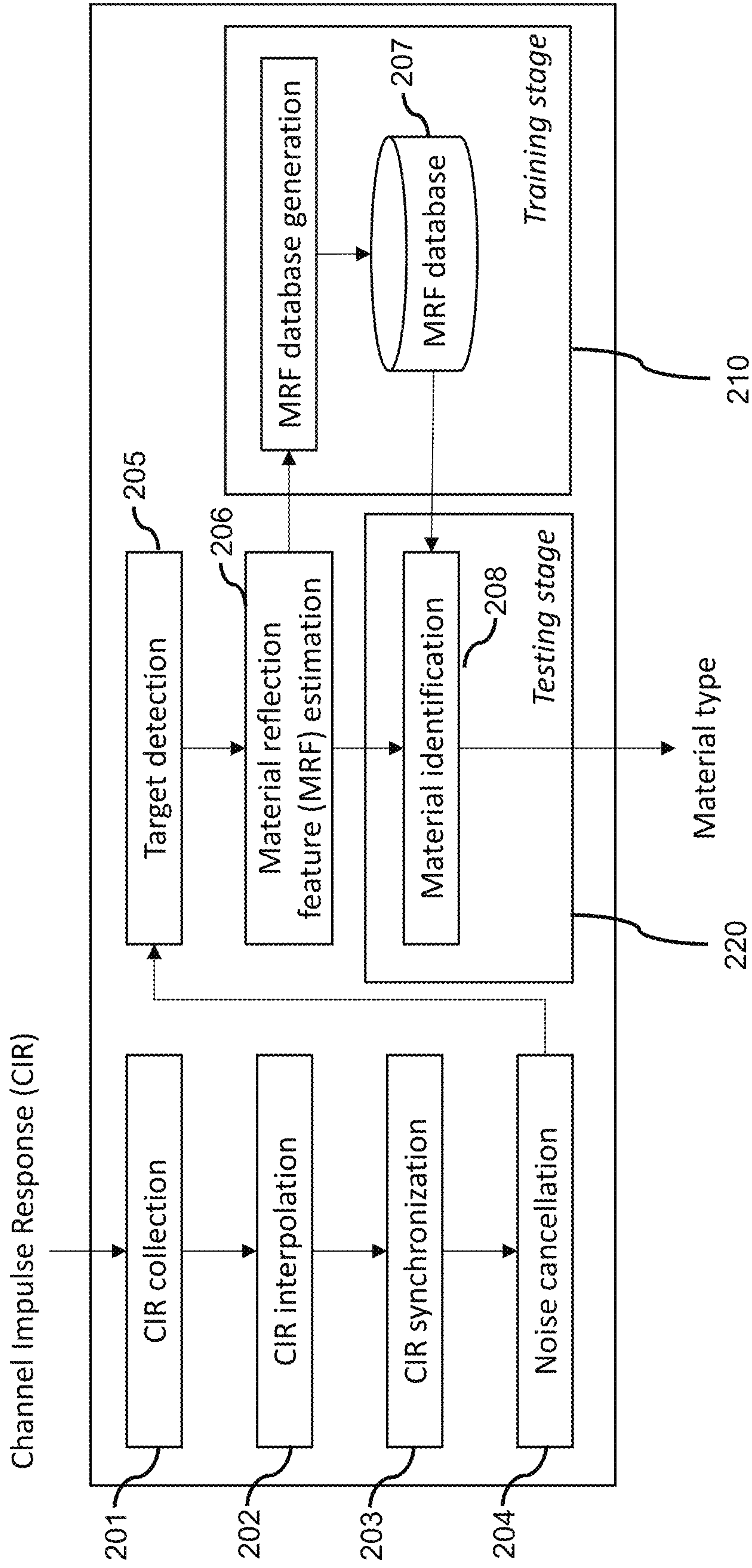


FIG. 1B

200



**FIG. 2**

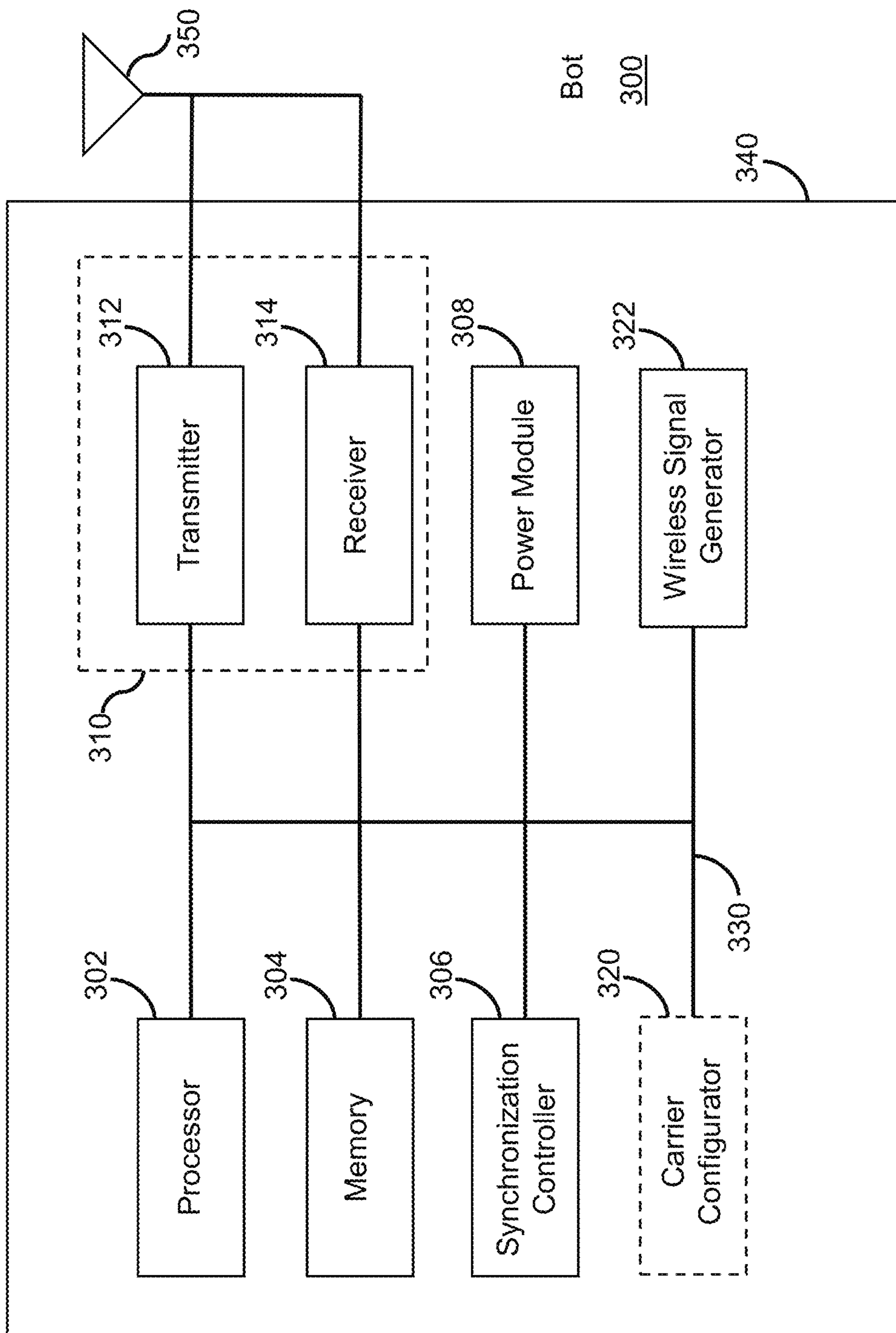


FIG. 3

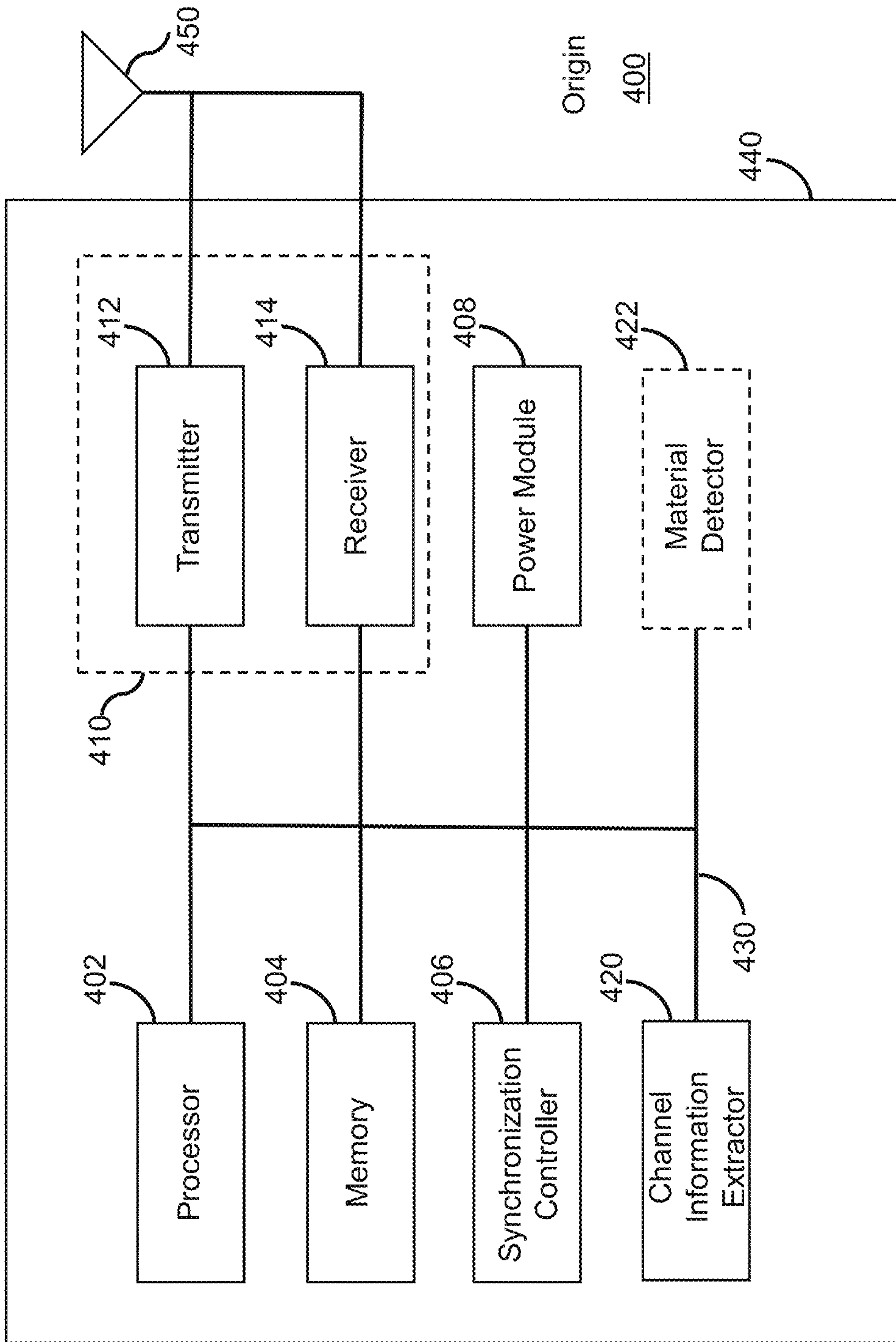
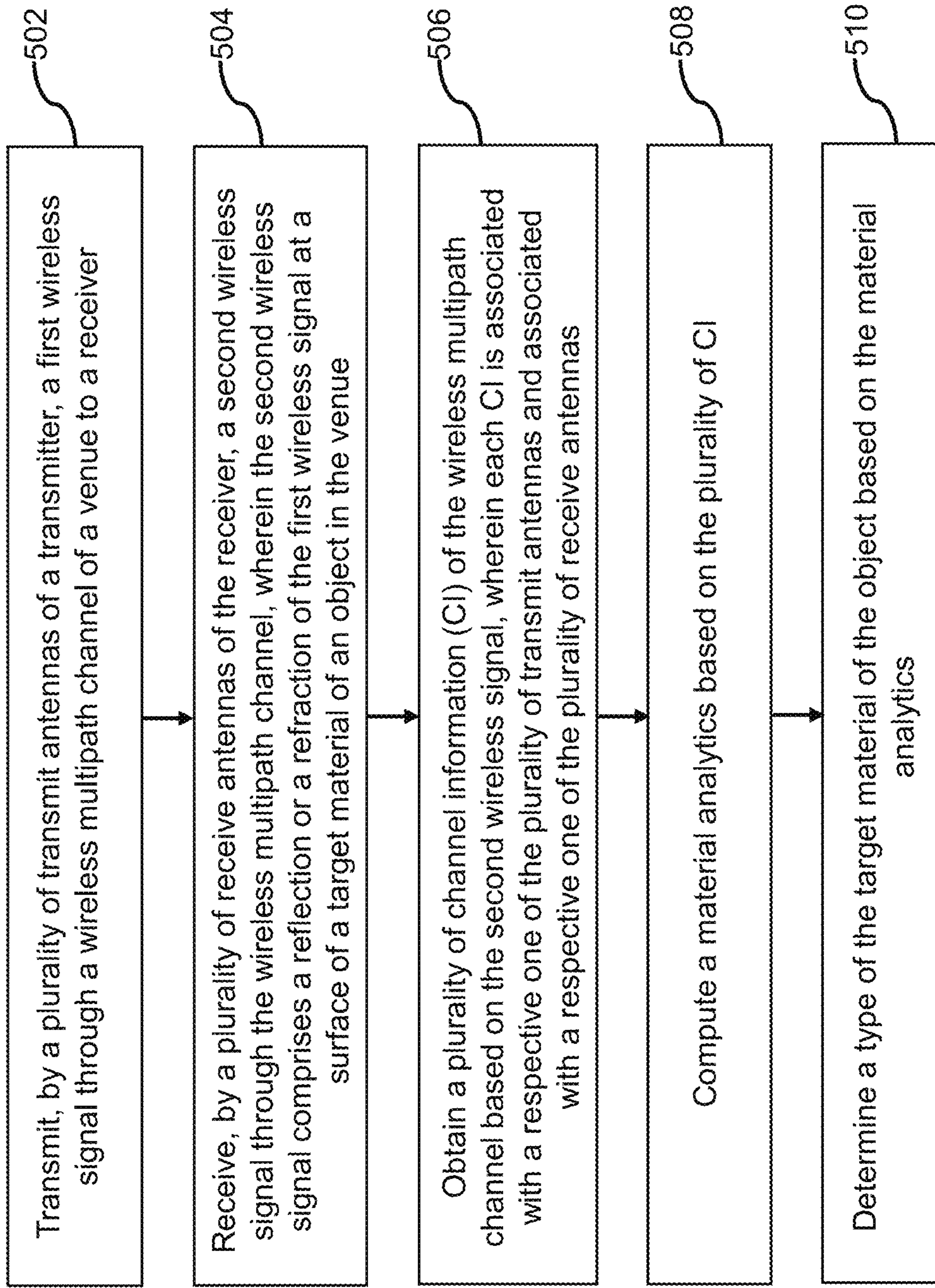


FIG. 4

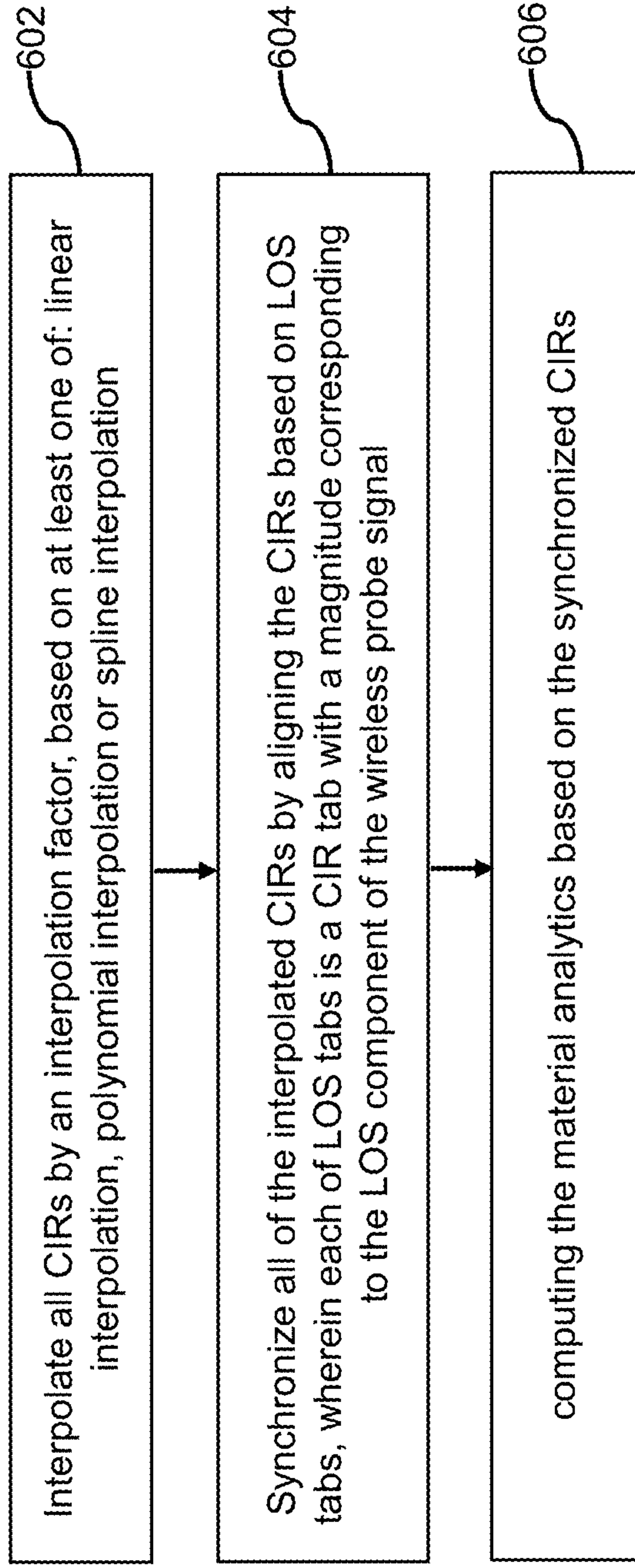
500



**FIG. 5**

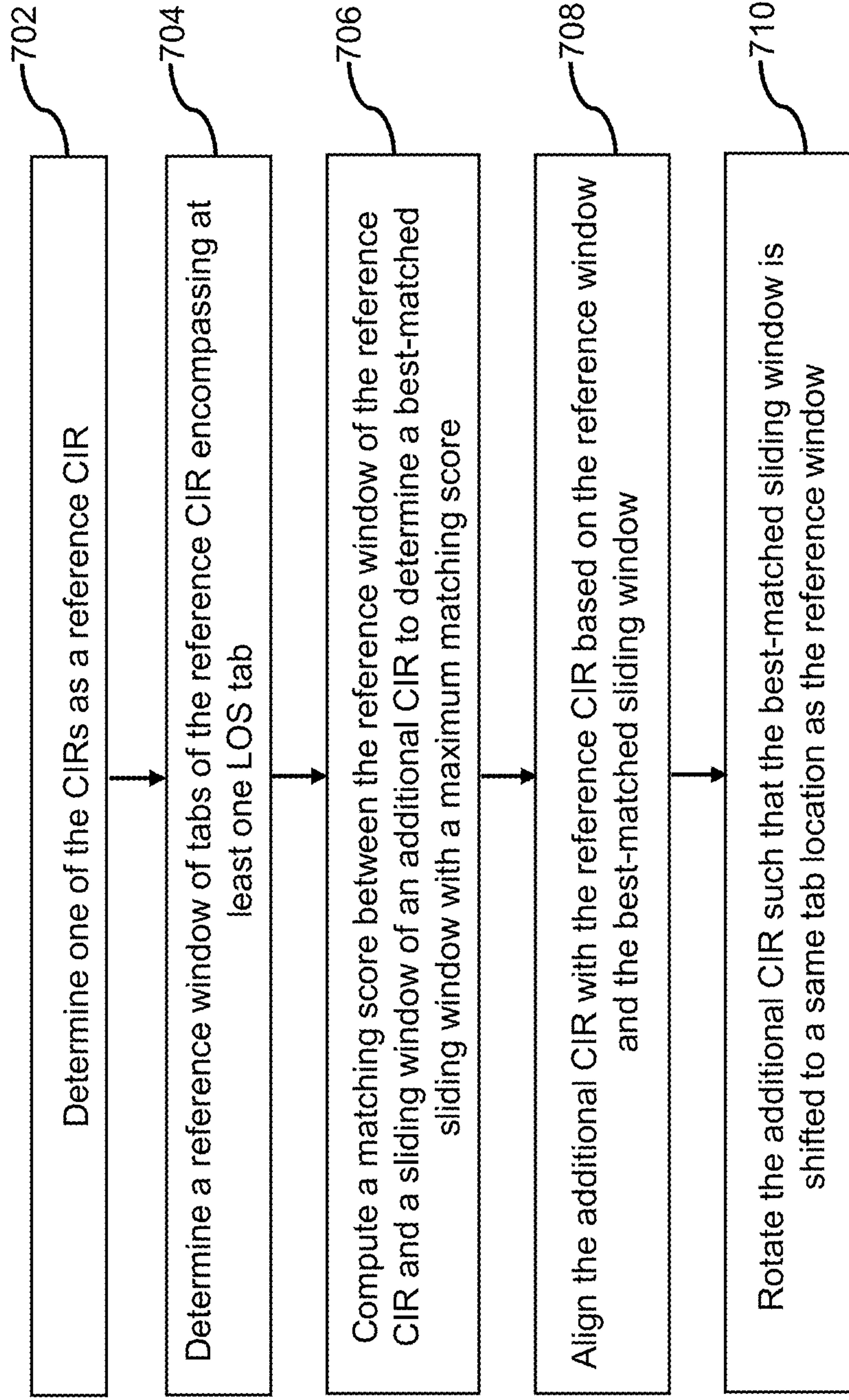


600



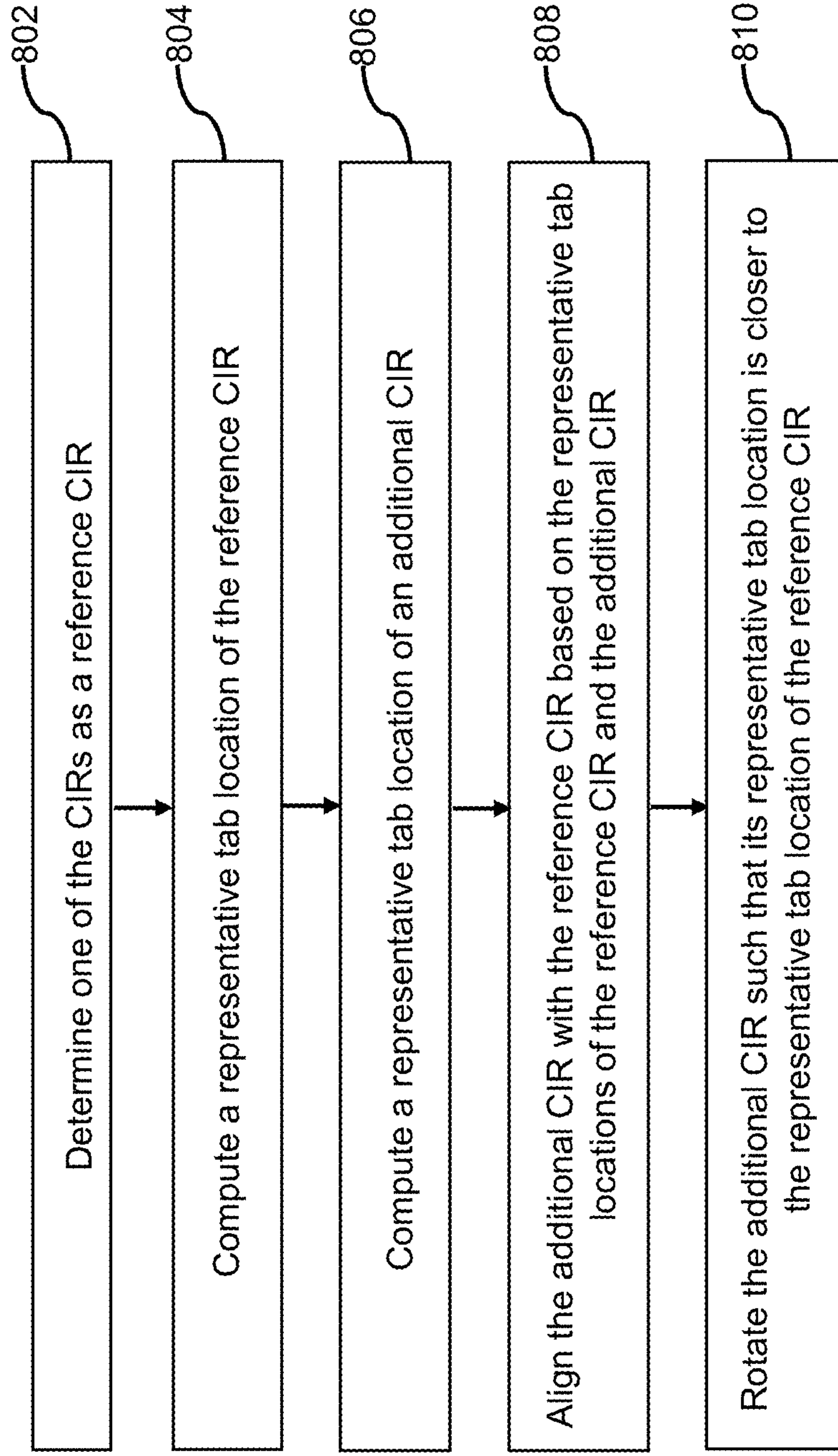
**FIG. 6**

700



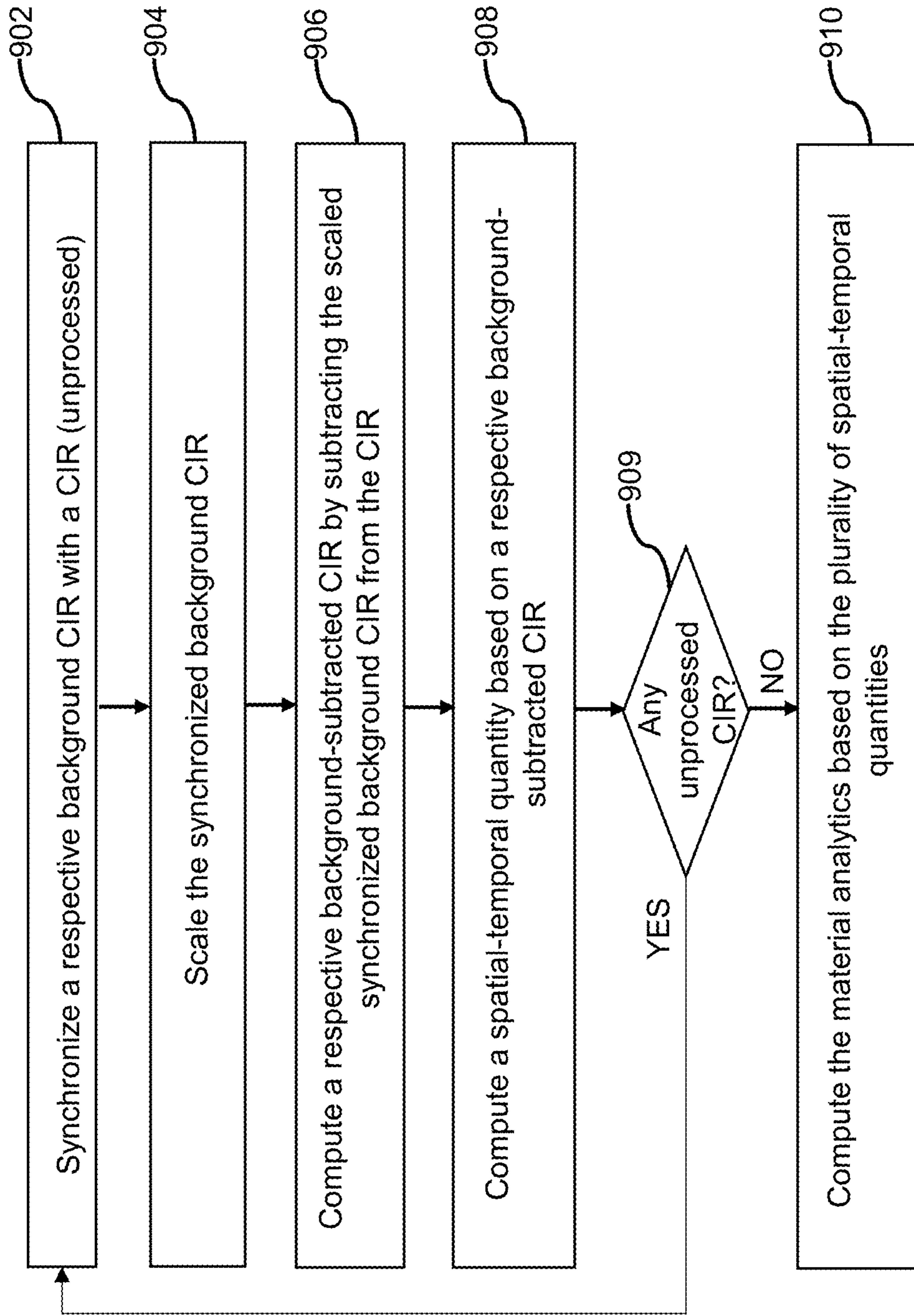
**FIG. 7**

800



**FIG. 8**

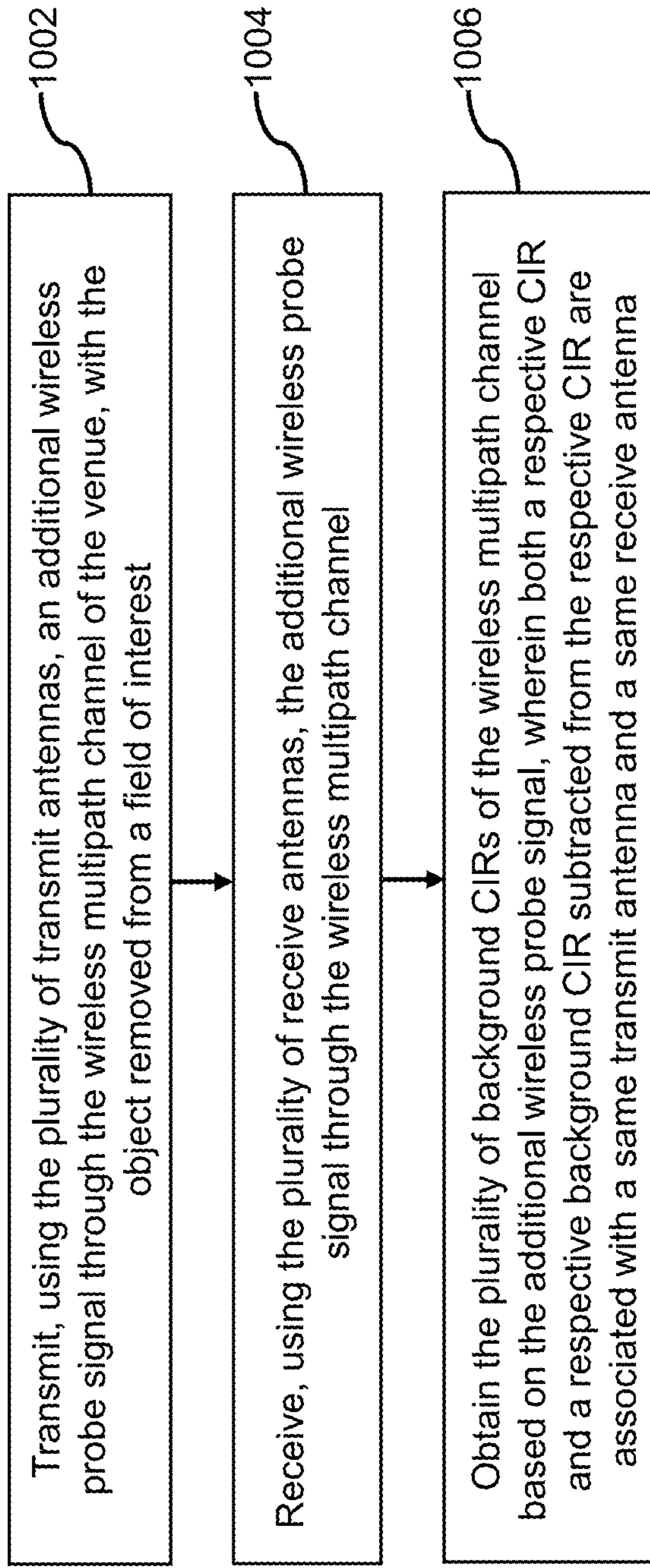
900



**FIG. 9**



1000



**FIG. 10**

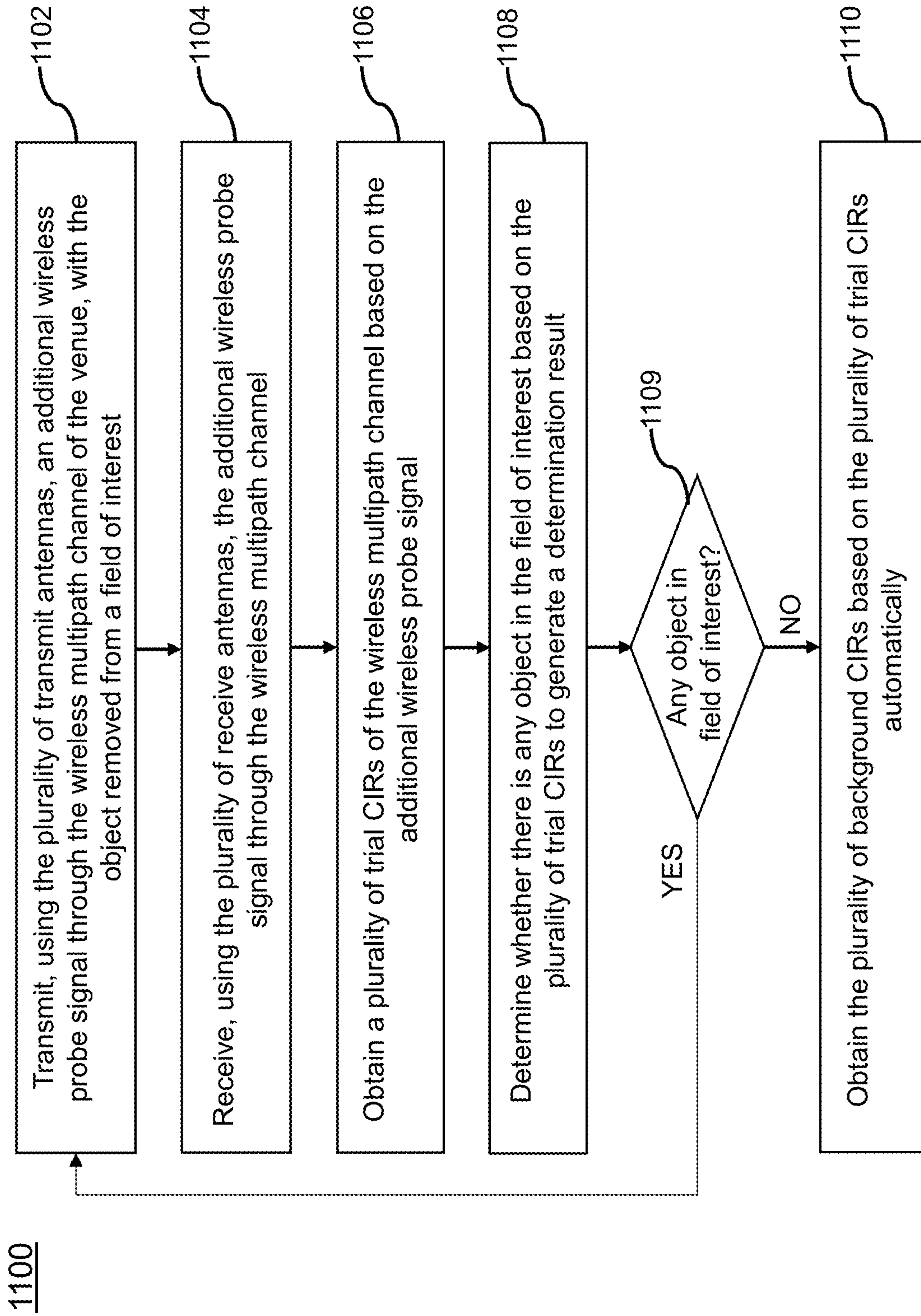
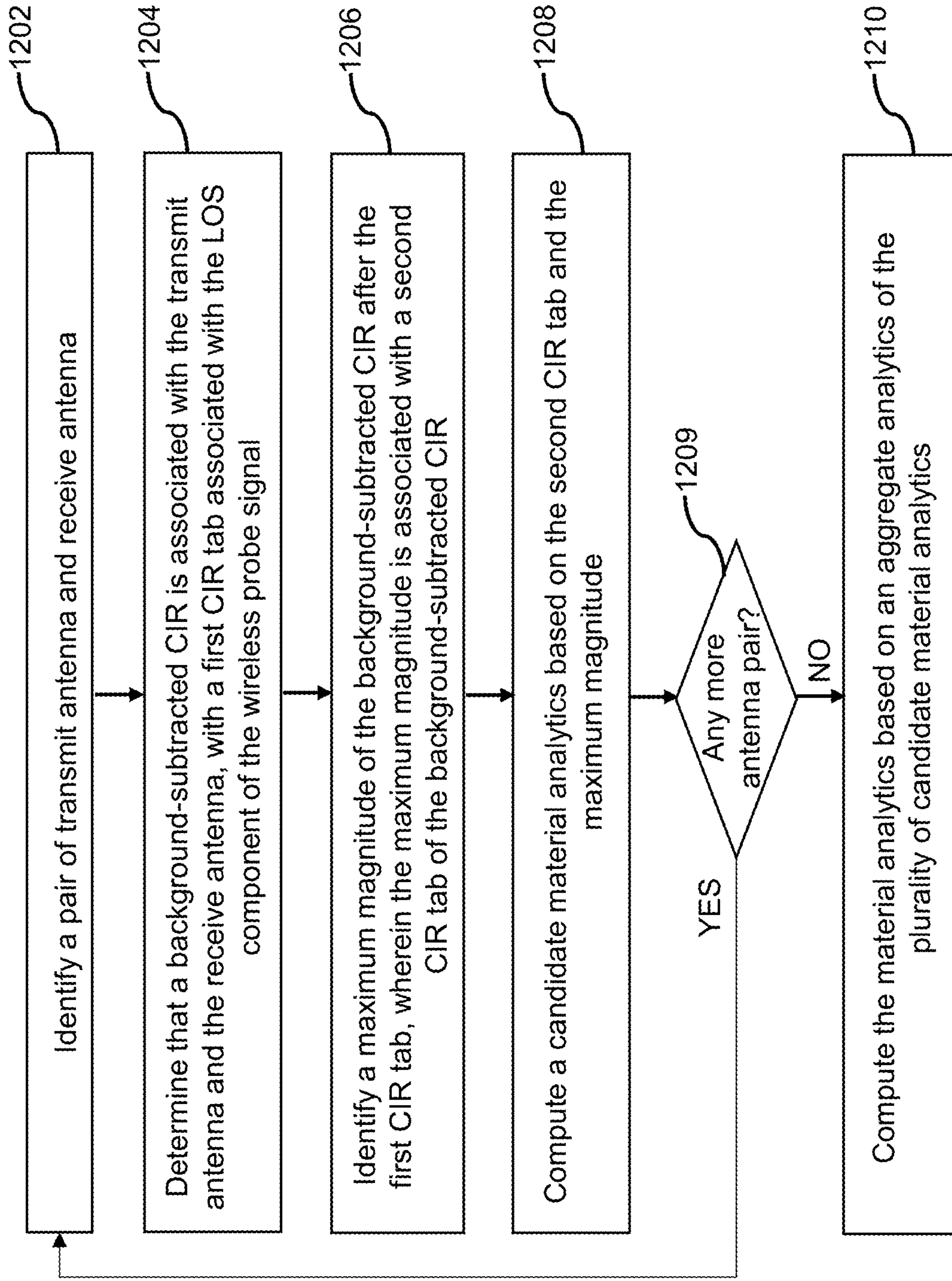


FIG. 11

1200



**FIG. 12**



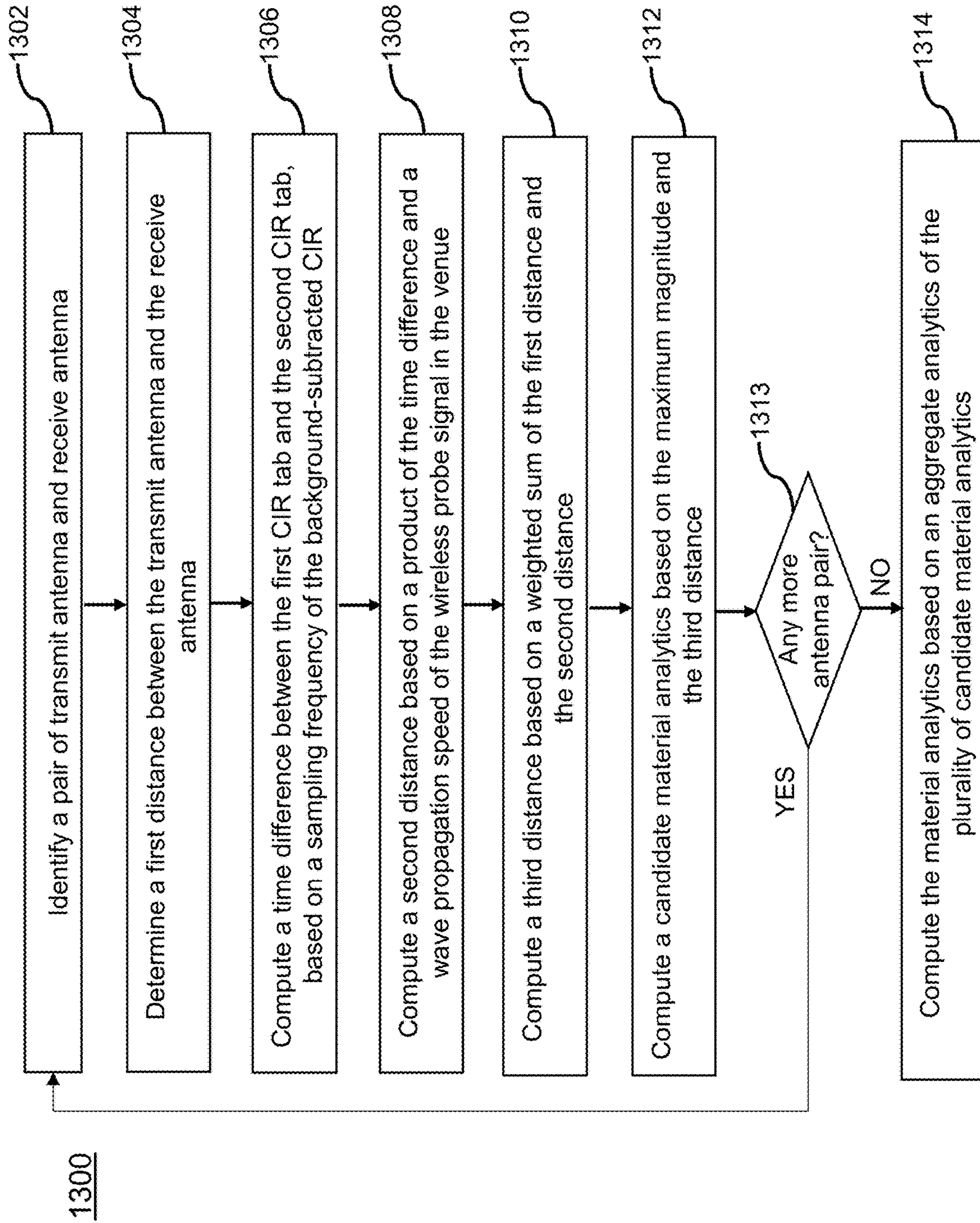


FIG. 13



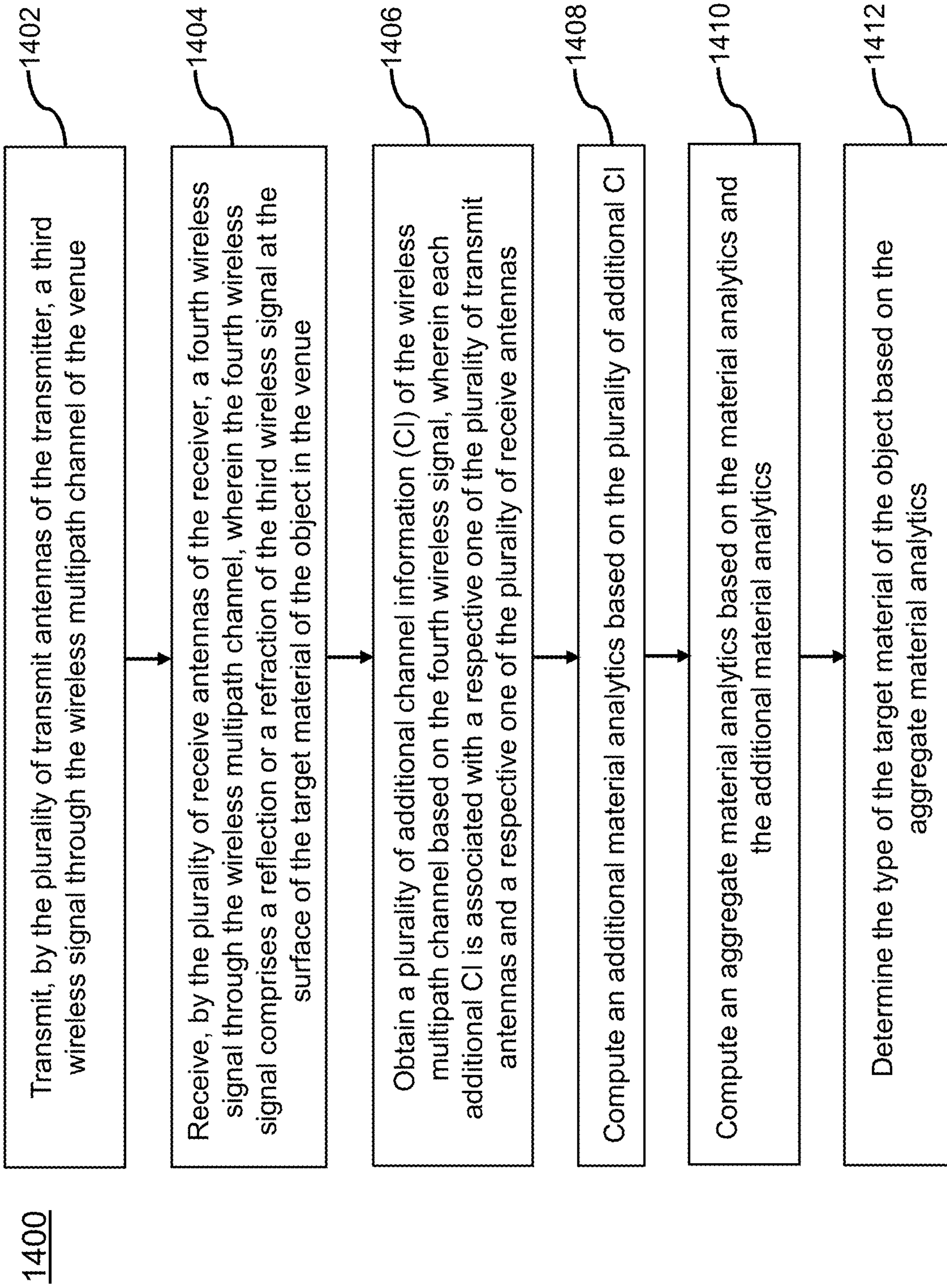


FIG. 14

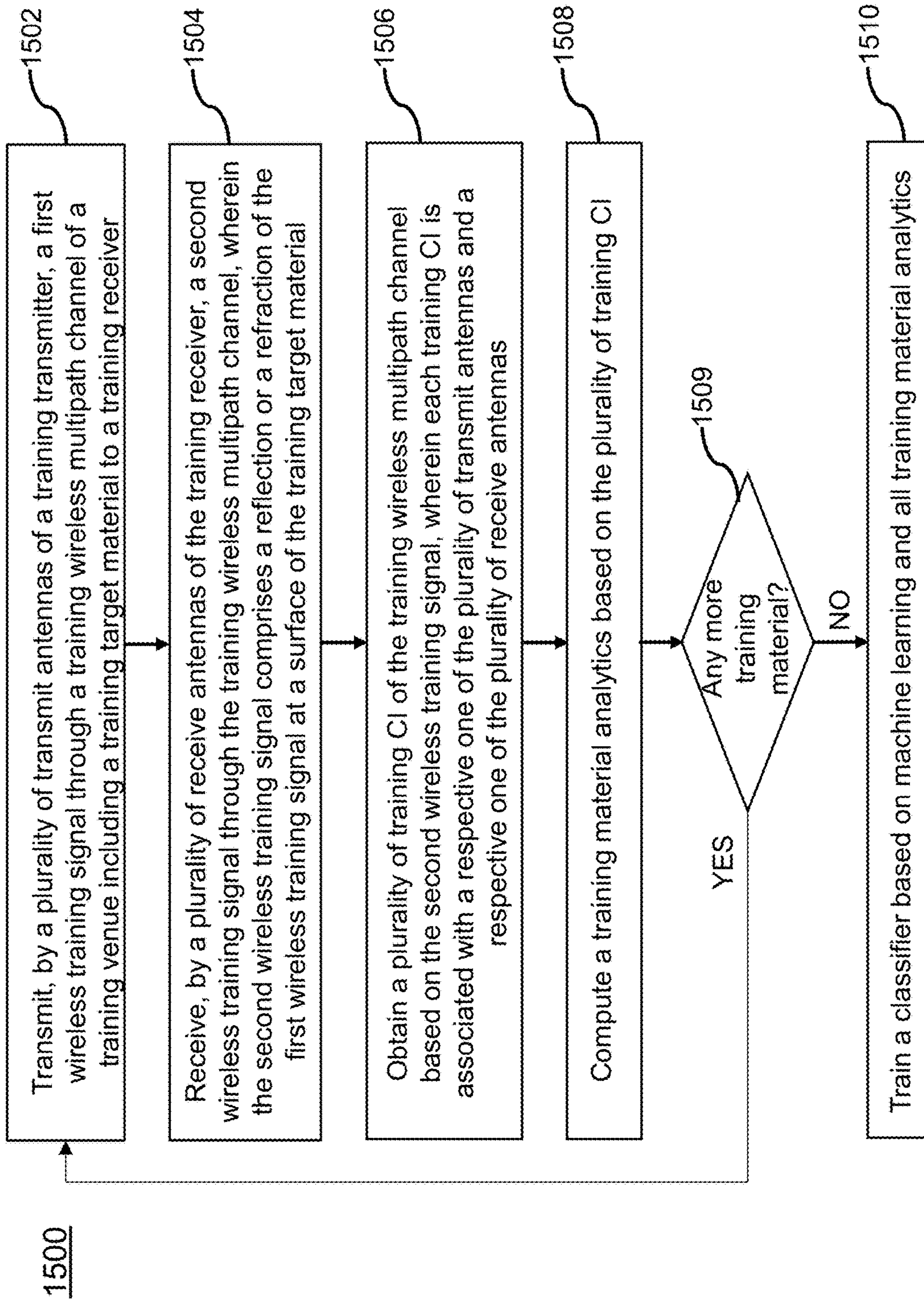


FIG. 15

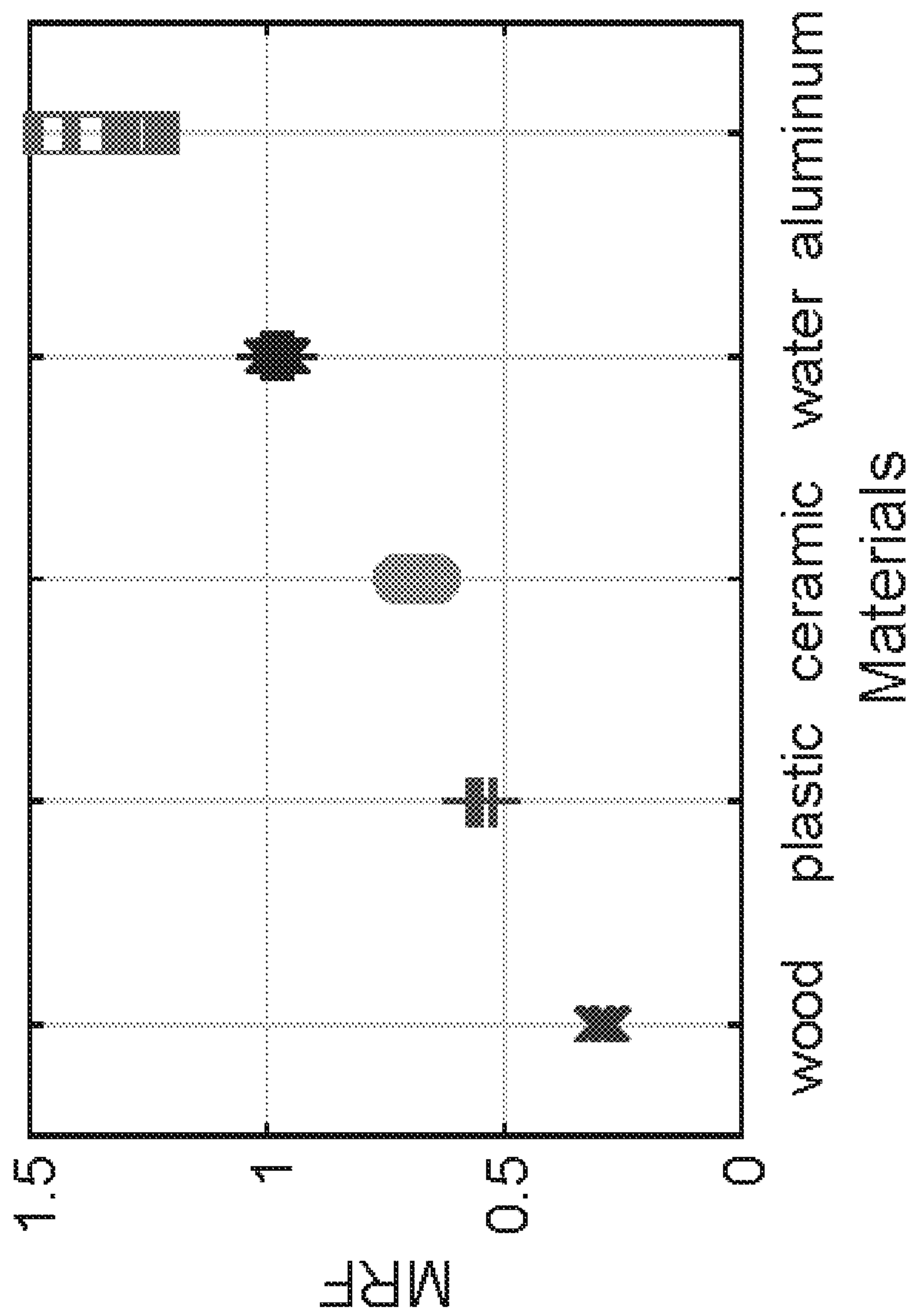


FIG. 16



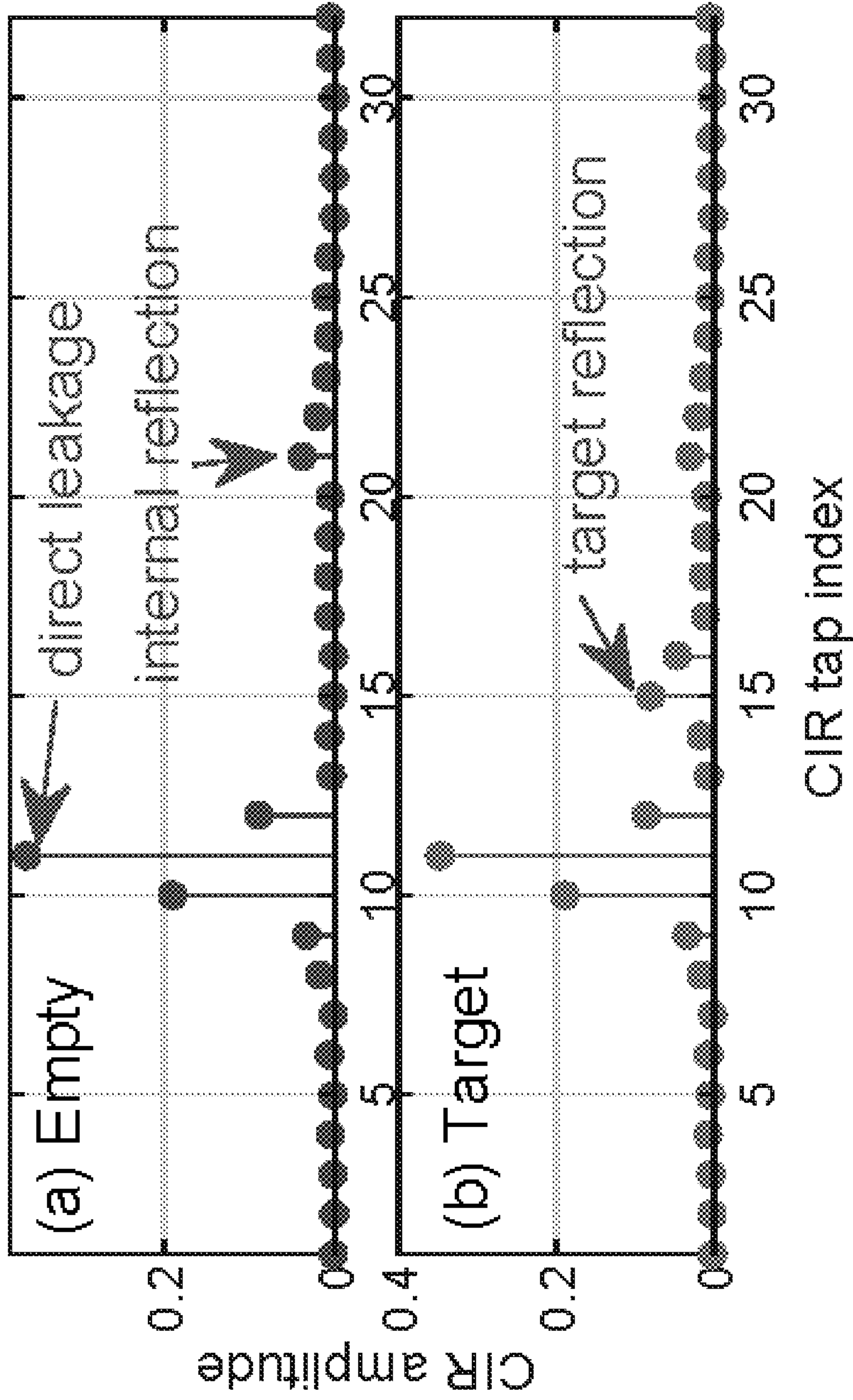


FIG. 17



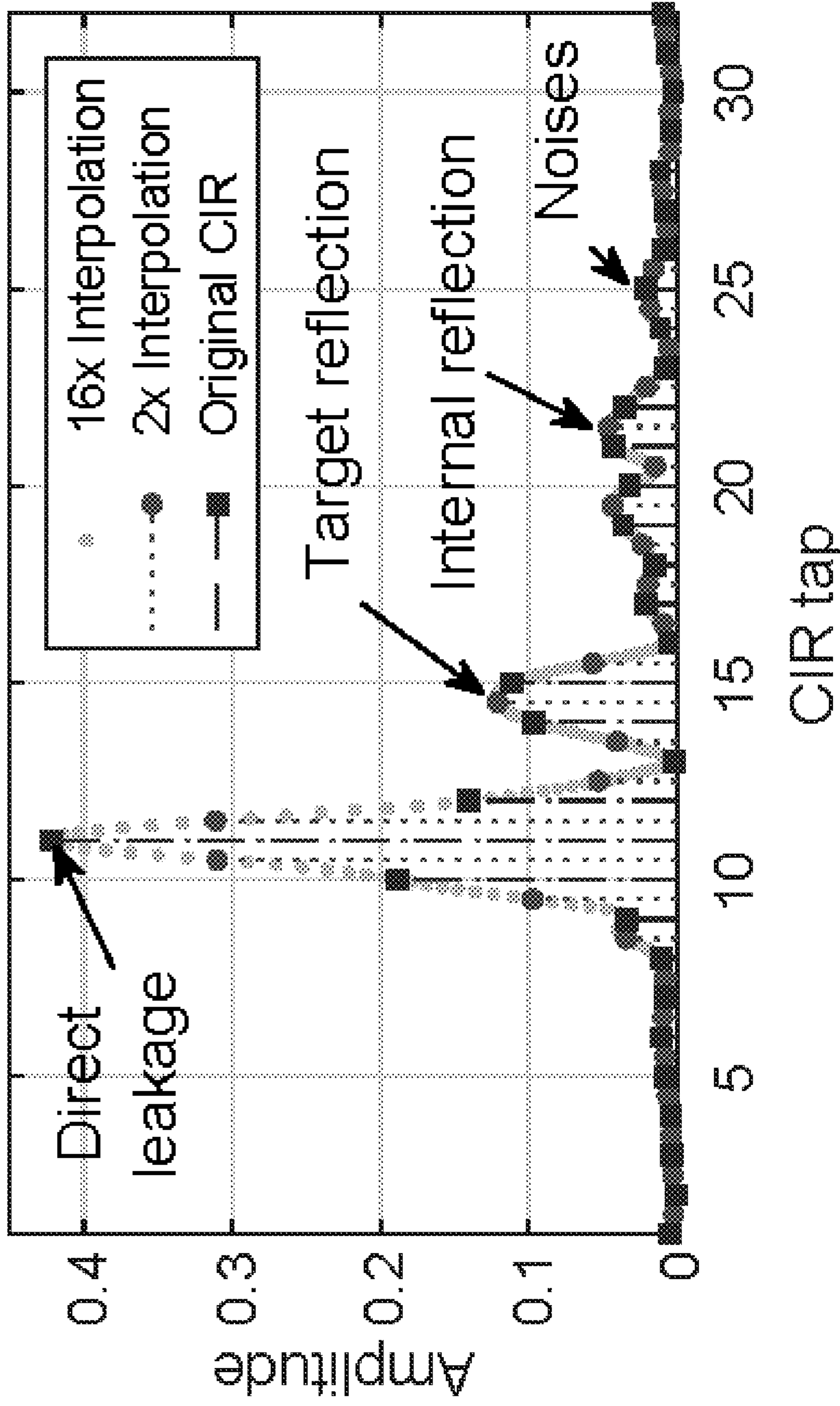


FIG. 18A

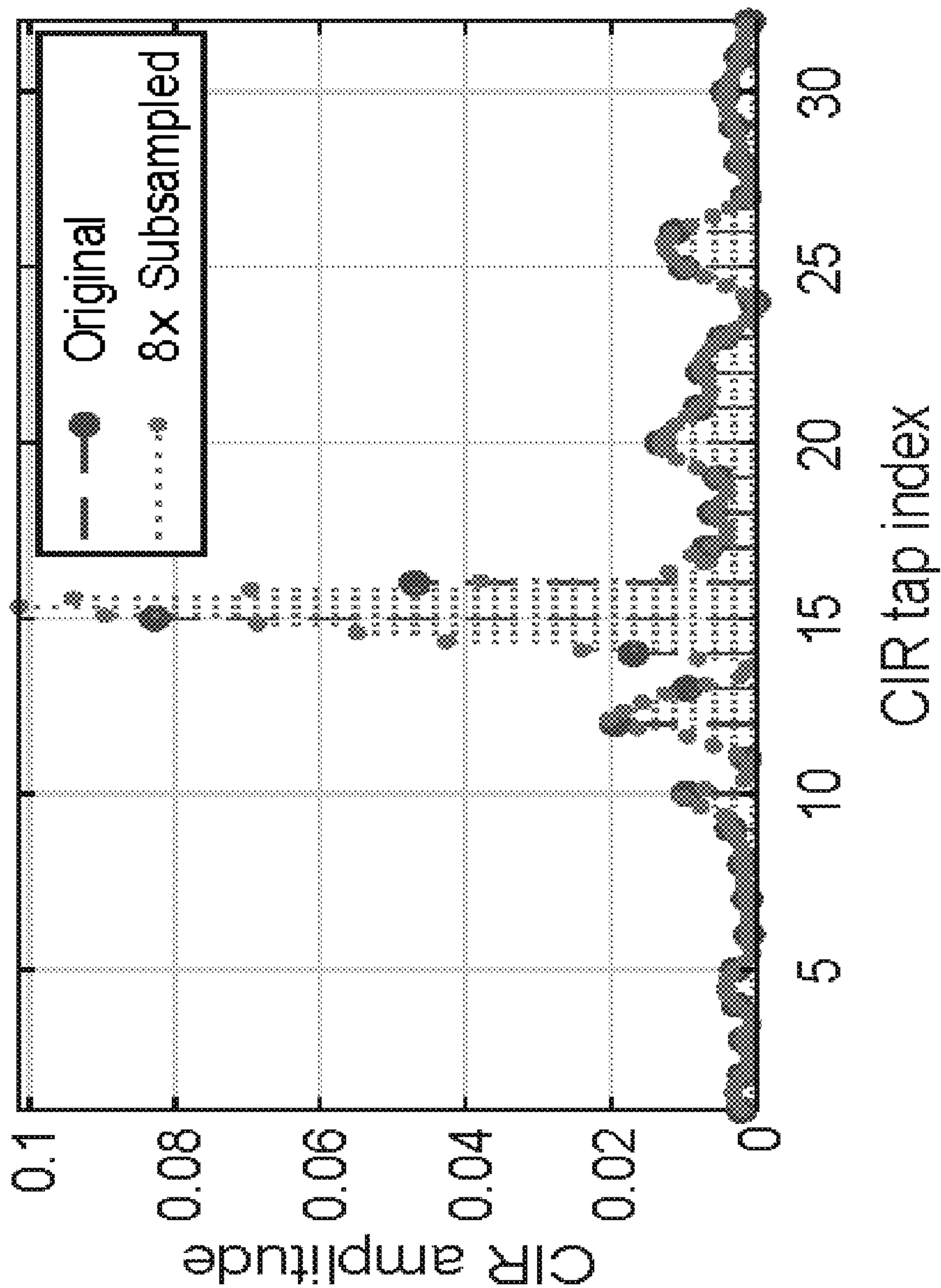


FIG. 18B

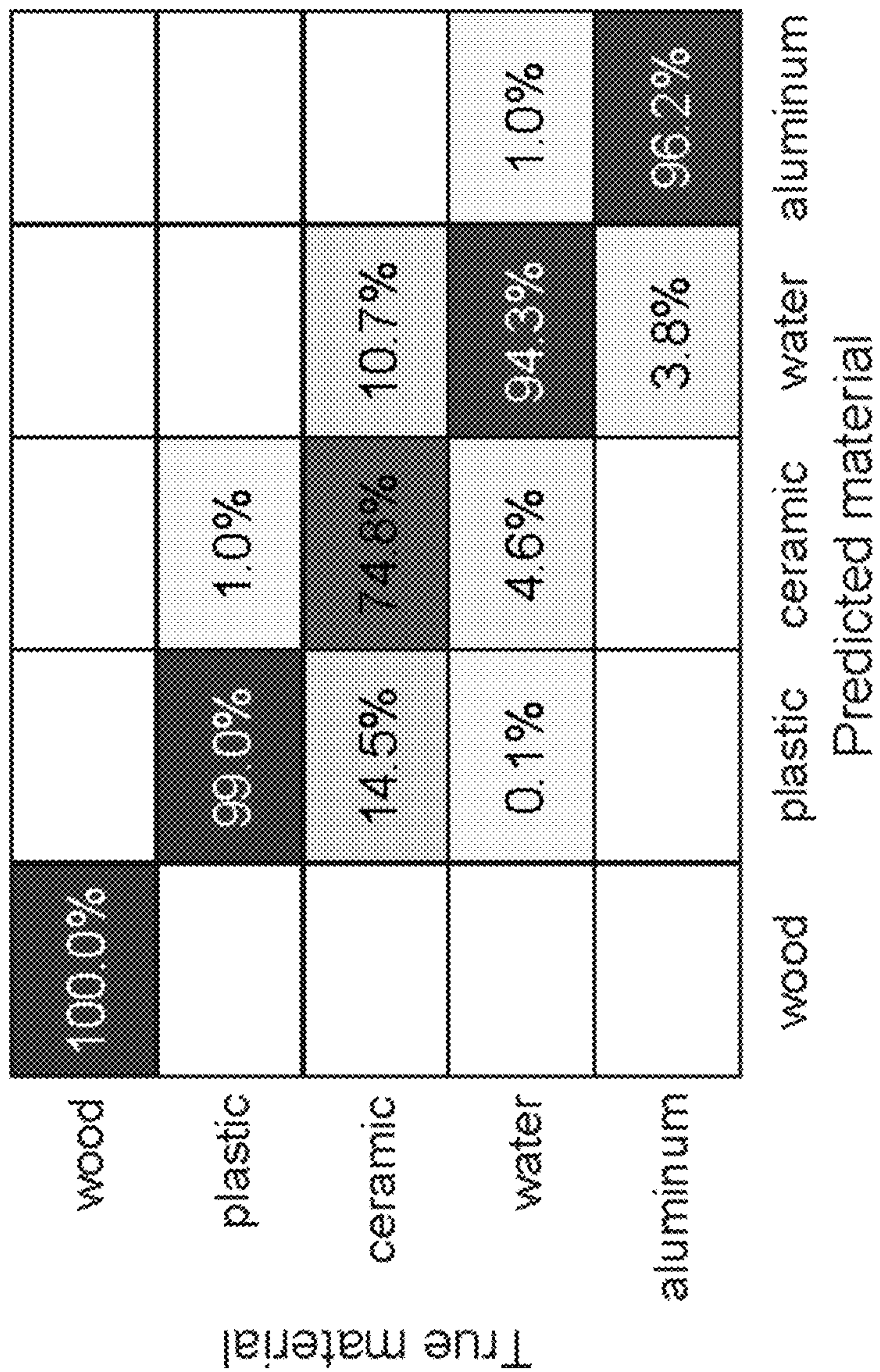


FIG. 19A



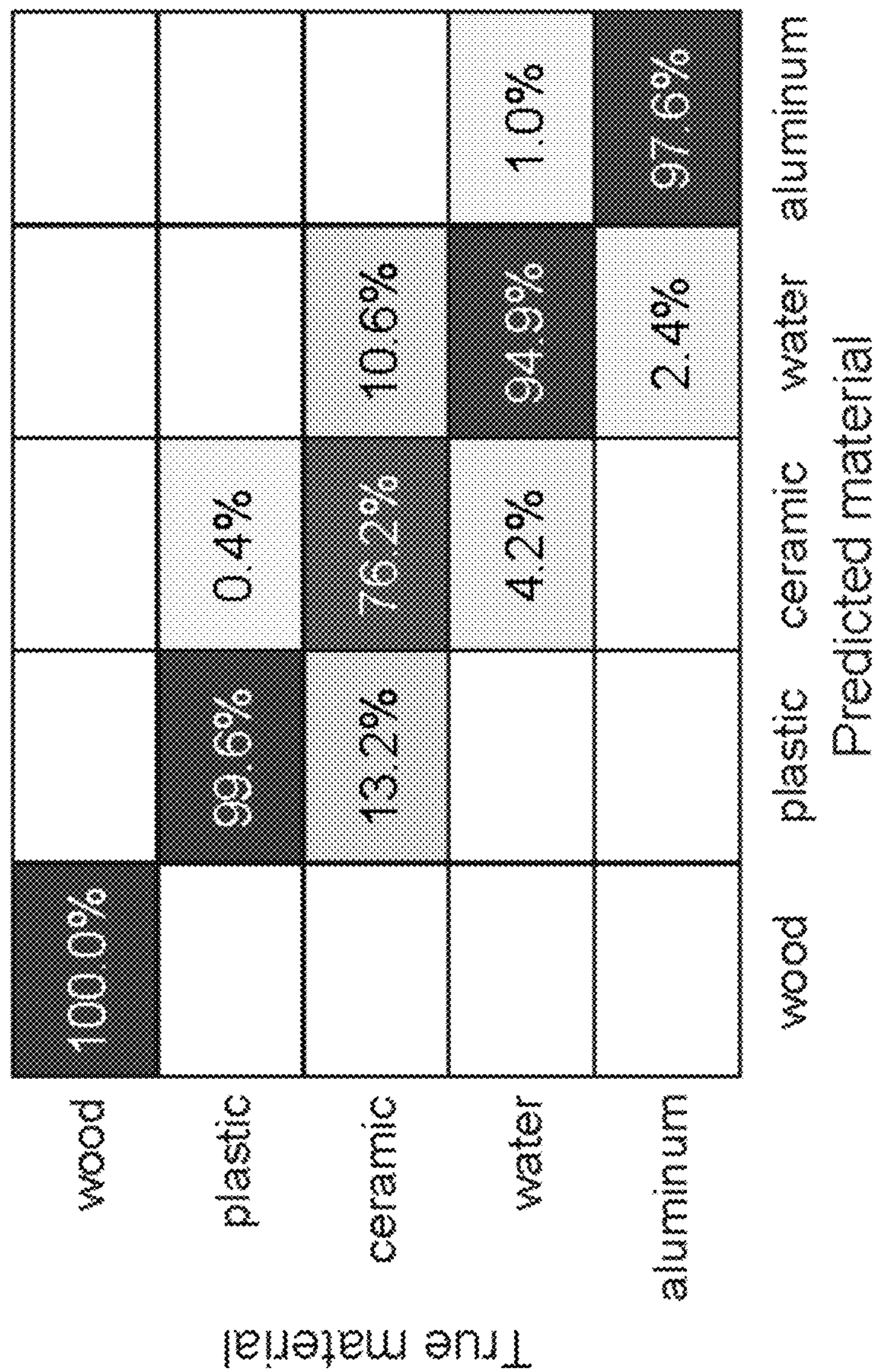


FIG. 19B



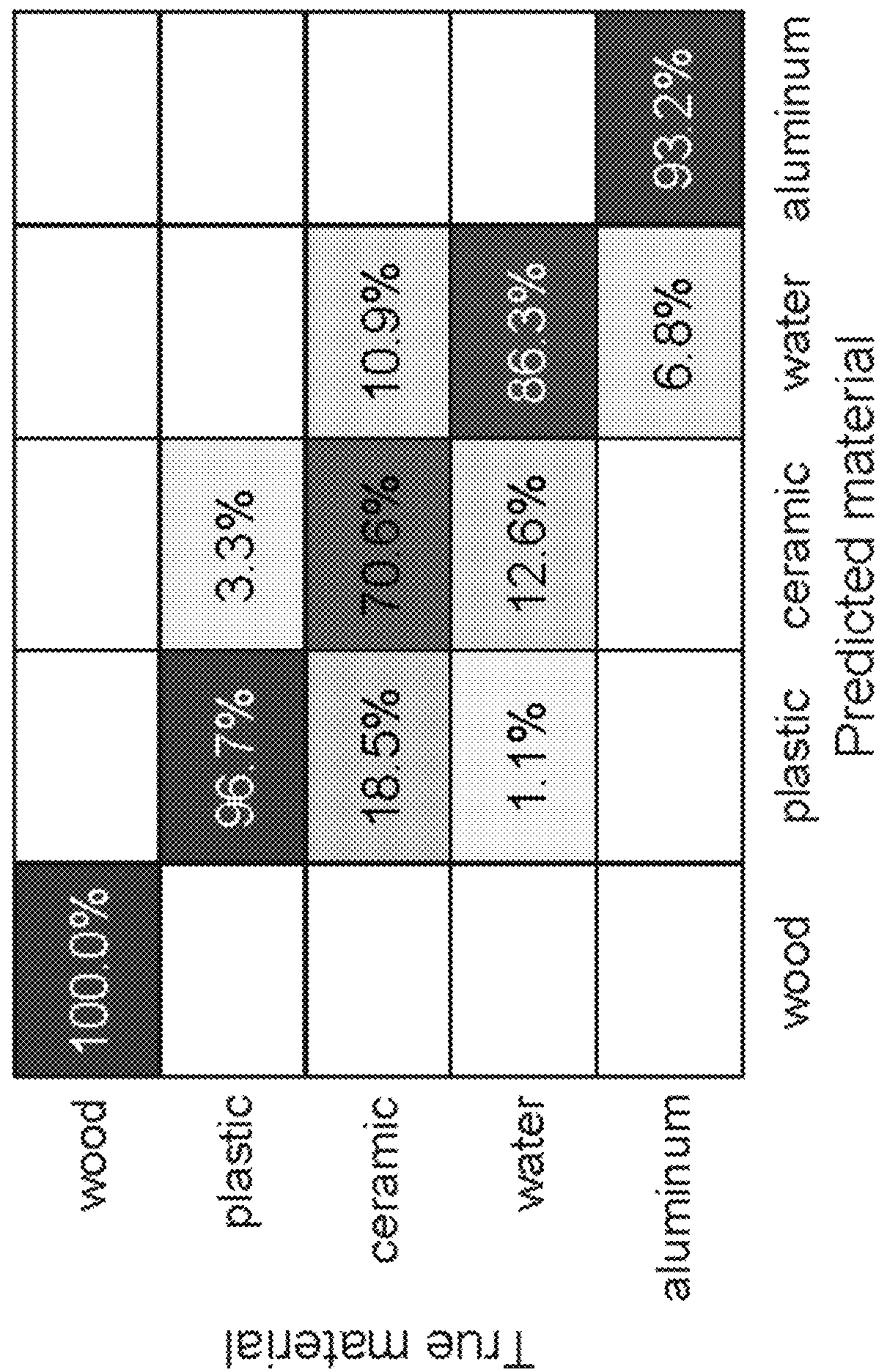


FIG. 19C



**METHOD, APPARATUS, AND SYSTEM FOR WIRELESS MATERIAL SENSING**

## CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is related to U.S. patent application Ser. No. 17/180,762, entitled "METHOD, APPARATUS, AND SYSTEM FOR FALL-DOWN DETECTION BASED ON A WIRELESS SIGNAL," filed on Feb. 20, 2021, related to U.S. patent application Ser. No. 17/180,763, entitled "METHOD, APPARATUS, AND SYSTEM FOR WIRELESS WRITING TRACKING," filed on Feb. 20, 2021, and related to U.S. patent application Ser. No. 17/180,766, entitled "METHOD, APPARATUS, AND SYSTEM FOR WIRELESS MOTION RECOGNITION," filed on Feb. 20, 2021, each of which is expressly incorporated by reference herein in its entirety.

The present application hereby incorporates by reference the entirety of the disclosures of, and claims priority to, each of the following cases:

- (a) U.S. patent application Ser. No. 15/326,112, entitled "WIRELESS POSITIONING SYSTEMS", filed on Jan. 13, 2017,
- (1) which is a national stage entry of PCT patent application PCT/US2015/041037, entitled "WIRELESS POSITIONING SYSTEMS", filed on Jul. 17, 2015, published as WO 2016/011433A2 on Jan. 21, 2016,
- (b) U.S. patent application Ser. No. 16/127,151, entitled "METHODS, APPARATUS, SERVERS, AND SYSTEMS FOR VITAL SIGNS DETECTION AND MONITORING", filed on Sep. 10, 2018, now U.S. Pat. No. 11,012,285,
- (1) which is a continuation-in-part of PCT patent application PCT/US2017/021963, entitled "METHODS, APPARATUS, SERVERS, AND SYSTEMS FOR VITAL SIGNS DETECTION AND MONITORING", filed on Mar. 10, 2017, published as W02017/1156492A1 on Sep. 14, 2017,
- (c) U.S. patent application Ser. No. 15/861,422, entitled "METHOD, APPARATUS, SERVER, AND SYSTEMS OF TIME-REVERSAL TECHNOLOGY", filed on Jan. 3, 2018, now U.S. Pat. No. 11,025,475,
- (d) U.S. patent application Ser. No. 16/667,648, entitled "METHOD, APPARATUS, AND SYSTEM FOR WIRELESS PROXIMITY AND PRESENCE MONITORING", filed on Oct. 29, 2019, now U.S. Pat. No. 11,035,940,
- (e) U.S. patent application Ser. No. 16/667,757, entitled "METHOD, APPARATUS, AND SYSTEM FOR HUMAN IDENTIFICATION BASED ON HUMAN RADIO BIOMETRIC INFORMATION", filed on Oct. 29, 2019,
- (f) U.S. Provisional Patent application 62/950,093, entitled "METHOD, APPARATUS, AND SYSTEM FOR TARGET POSITIONING", filed on Dec. 18, 2019,
- (g) U.S. patent application Ser. No. 16/790,610, entitled "METHOD, APPARATUS, AND SYSTEM FOR WIRELESS GAIT RECOGNITION", filed Feb. 13, 2020,
- (h) U.S. patent application Ser. No. 16/790,627, entitled "METHOD, APPARATUS, AND SYSTEM FOR OUTDOOR TARGET TRACKING", filed Feb. 13, 2020.
- (i) U.S. Provisional Patent application 62/977,326, entitled "METHOD, APPARATUS, AND SYSTEM

FOR AUTOMATIC AND ADAPTIVE WIRELESS MONITORING AND TRACKING", filed on Feb. 16, 2020,

- (j) U.S. patent application Ser. No. 16/798,343, entitled "METHOD, APPARATUS, AND SYSTEM FOR WIRELESS OBJECT TRACKING", filed Feb. 22, 2020,
- (k) U.S. Provisional Patent application 62/980,206, entitled "METHOD, APPARATUS, AND SYSTEM FOR WIRELESS SENSING", filed on Feb. 22, 2020,
- (l) U.S. Provisional Patent application 62/981,387, entitled "METHOD, APPARATUS, AND SYSTEM FOR VEHICLE WIRELESS MONITORING", filed on Feb. 25, 2020,
- (m) U.S. Provisional Patent application 62/984,737, entitled "METHOD, APPARATUS, AND SYSTEM FOR IMPROVED WIRELESS MONITORING", filed on Mar. 3, 2020,
- (n) U.S. Provisional Patent application 63/001,226, entitled "METHOD, APPARATUS, AND SYSTEM FOR IMPROVED WIRELESS MONITORING AND USER INTERFACE", filed on Mar. 27, 2020,
- (o) U.S. patent application Ser. No. 16/871,000, entitled "METHOD, APPARATUS, AND SYSTEM FOR WIRELESS TRACKING WITH GRAPH-BASED PARTICLE FILTERING", filed on May 10, 2020,
- (p) U.S. patent application Ser. No. 16/871,004, entitled "METHOD, APPARATUS, AND SYSTEM FOR PEOPLE COUNTING AND RECOGNITION BASED ON RHYTHMIC MOTION MONITORING", filed on May 10, 2020,
- (q) U.S. patent application Ser. No. 16/871,006, entitled "METHOD, APPARATUS, AND SYSTEM FOR VITAL SIGNS MONITORING USING HIGH FREQUENCY WIRELESS SIGNALS", filed on May 10, 2020,
- (r) U.S. Provisional Patent application 63/038,037, entitled "METHOD, APPARATUS, AND SYSTEM FOR MOTION LOCALIZATION, WALKING DETECTION AND DEVICE QUALIFICATION", filed on Jun. 11, 2020,
- (s) U.S. patent application Ser. No. 16/909,913, entitled "METHOD, APPARATUS, AND SYSTEM FOR IMPROVING TOPOLOGY OF WIRELESS SENSING SYSTEMS", filed on Jun. 23, 2020,
- (t) U.S. patent application 16/909,940, entitled "METHOD, APPARATUS, AND SYSTEM FOR QUALIFIED WIRELESS SENSING", filed on Jun. 23, 2020,
- (u) U.S. patent application 16/945,827, entitled "METHOD, APPARATUS, AND SYSTEM FOR PROCESSING AND PRESENTING LIFE LOG BASED ON A WIRELESS SIGNAL" filed on Aug. 1, 2020,
- (v) U.S. patent application Ser. No. 16/945,837, entitled "METHOD, APPARATUS, AND SYSTEM FOR WIRELESS SLEEP MONITORING", filed on Aug. 1, 2020,
- (w) U.S. patent application Ser. No. 17/019,273, entitled "METHOD, APPARATUS, AND SYSTEM FOR AUTOMATIC AND ADAPTIVE WIRELESS MONITORING AND TRACKING", filed on Sep. 13, 2020,
- (x) U.S. patent application Ser. No. 17/019,271, entitled "METHOD, APPARATUS, AND SYSTEM FOR POSITIONING AND POWERING A WIRELESS MONITORING SYSTEM", filed on Sep. 13, 2020,



- (y) U.S. patent application Ser. No. 17/019,270, entitled “METHOD, APPARATUS, AND SYSTEM FOR VEHICLE WIRELESS MONITORING”, filed on Sep. 13, 2020,
- (z) U.S. Provisional Patent application 63/087,122, entitled “METHOD, APPARATUS, AND SYSTEM FOR WIRELESS TRACKING”, filed on Oct. 2, 2020,
- (aa) U.S. Provisional Patent application 63/090,670, entitled “METHOD, APPARATUS, AND SYSTEM FOR WIRELESS MONITORING TO ENSURE SECURITY”, filed on Oct. 12, 2020,
- (bb) U.S. Provisional Patent application 63/104,422, entitled “METHOD, APPARATUS, AND SYSTEM FOR WIRELESS MONITORING”, filed on Oct. 22, 2020,
- (cc) U.S. Provisional Patent application 63/112,563, entitled “METHOD, APPARATUS, AND SYSTEM FOR WIRELESS MONITORING BASED ON ANTENNA ARRANGEMENT”, filed on Nov. 11, 2020,
- (dd) U.S. patent application Ser. No. 17/113,024, entitled “METHOD APPARATUS, AND SYSTEM FOR PROVIDING AUTOMATIC ASSISTANCE BASED ON WIRELESS MONITORING”, filed on Dec. 5, 2020,
- (ee) U.S. patent application Ser. No. 17/113,023, entitled “METHOD APPARATUS, AND SYSTEM FOR ACCURATE WIRELESS MONITORING”, filed on Dec. 5, 2020,
- (ff) U.S. patent application Ser. No. 17/149,625, entitled “METHOD, APPARATUS, AND SYSTEM FOR WIRELESS MONITORING WITH MOTION LOCALIZATION”, filed on Jan. 14, 2021,
- (gg) U.S. patent application Ser. No. 17/149,667, entitled “METHOD, APPARATUS, AND SYSTEM FOR WIRELESS MONITORING WITH FLEXIBLE POWER SUPPLY”, filed on Jan. 14, 2021.

#### TECHNICAL FIELD

The present teaching generally relates to wireless sensing. More specifically, the present teaching relates to sensing and detecting material based on radio frequency wireless signals by processing wireless channel information (CI).

#### BACKGROUND

Efforts have been made to enable material identification on ubiquitous computing machines. In recent years, the proliferation of autonomous devices (e.g., self-driving vehicles, drones), in-home robots (e.g., robot vacuum cleaner, elder care robots) and other smart devices has further driven such demand of object imaging and material identification in mobile environments. Should it be enabled on ubiquitous devices, there could be many applications, ranging from security to automotive and robotics. For example, the capability of material sensing would allow a user to perform convenient in-home detection of a suspicious package containing metals or liquids using a smartphone. A robot could actuate more appropriately by accounting for the target material, e.g., applying different grip strengths for ceramic or metal targets. Further, a smart pencil or a kid educational toy could be enabled to react intelligently with specific functions according to the things it touches or points to. All these exciting applications and many more to be imagined necessitate ubiquitous object material identification in an accurate, portable, and low-cost setting.

Conventional systems, however, usually rely on specialized hardware like X-Ray and ultrasonography and are limited to only critical security and medical usage, which prevents them from ubiquitous adoption outside a lab environment. Recently, radio-frequency identification (RFID) tags are deployed for material identification, while ultra-wideband (UWB) signals are employed to identify liquids. These systems, however, usually rely on multiple transceivers locating on different sides of the target to measure the signals penetrating it, limiting their applications to only fixed, constrained setups and to objects that radio-frequency (RF) signals can penetrate through. Some other systems require specialized radars or mutually orthogonal antennas.

#### SUMMARY

The present teaching generally relates to wireless sensing. More specifically, the present teaching relates to sensing and detecting material based on radio frequency wireless signals by processing wireless channel information (CI).

In one embodiment, a system for wireless material sensing is described. The system comprises: a transmitter configured for transmitting, using a plurality of transmit antennas, a first wireless signal through a wireless multipath channel of a venue; a receiver configured for receiving, using a plurality of receive antennas, a second wireless signal through the wireless multipath channel; and a processor. The second wireless signal comprises a reflection or a refraction of the first wireless signal at a target material surface of an object in the venue. The target material surface is a surface of a target material of the object. The processor is configured for: obtaining a plurality of channel information (CI) of the wireless multipath channel based on the second wireless signal, wherein each CI is associated with a respective one of the plurality of transmit antennas of the transmitter and associated with a respective one of the plurality of receive antennas of the receiver, wherein each CI comprises at least one of: a channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI); computing a material analytics based on the plurality of CI; and determining a type of the target material of the object based on the material analytics.

In another embodiment, a wireless device of a wireless material sensing system is described. The wireless device comprises: a processor; a memory communicatively coupled to the processor; and a receiver communicatively coupled to the processor. An additional wireless device of the wireless material sensing system is configured for transmitting, using a plurality of transmit antennas, a first wireless signal through a wireless multipath channel of a venue. The receiver is configured for receiving, using a plurality of receive antennas, a second wireless signal through the wireless multipath channel. The second wireless signal comprises a reflection or a refraction of the first wireless signal at a target material surface of an object in the venue. The target material surface is a surface of a target material of the object. The processor is configured for: obtaining a plurality of channel information (CI) of the wireless multipath channel based on the second wireless signal, wherein each CI is associated with a respective one of the plurality of transmit antennas and associated with a respective one of the plurality of receive antennas; computing a material analytics based on the plurality of CI; and determining a type of the target material of the object based on the material analytics.



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In yet another embodiment, a method of a wireless material sensing system is described. The method comprises: transmitting, using N1 transmit antennas of a transmitter, a first wireless signal through a wireless multipath channel of a venue; receiving, using N2 receive antennas of a receiver, a second wireless signal through the wireless multipath channel, wherein the second wireless signal comprises a reflection or a refraction of the first wireless signal at a surface of a target material of an object in the venue, wherein N1 and N2 are positive integers; obtaining a plurality of channel information (CI) of the wireless multipath channel based on the second wireless signal, wherein each CI is associated with a respective one of the N1 transmit antennas and associated with a respective one of the N2 receive antennas, wherein each CI comprises at least one of: a channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI); computing a material analytics based on the plurality of CI; and determining a type of the target material of the object based on the material analytics.

Other concepts relate to software for implementing the present teaching on wireless material sensing. Additional novel features will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art upon examination of the following and the accompanying drawings or may be learned by production or operation of the examples. The novel features of the present teachings may be realized and attained by practice or use of various aspects of the methodologies, instrumentalities and combinations set forth in the detailed examples discussed below.

## BRIEF DESCRIPTION OF DRAWINGS

The methods, systems, and/or devices described herein are further described in terms of exemplary embodiments. These exemplary embodiments are described in detail with reference to the drawings. These embodiments are non-limiting exemplary embodiments, in which like reference numerals represent similar structures throughout the several views of the drawings.

FIG. 1A illustrates an exemplary environment for wireless material sensing, according to some embodiments of the present disclosure.

FIG. 1B illustrates an exemplary scenario for wireless material sensing, according to some embodiments of the present disclosure.

FIG. 2 illustrates an exemplary workflow for wireless material sensing based on channel impulse response (CIR), according to some embodiments of the present disclosure.

FIG. 3 illustrates an exemplary block diagram of a first wireless device of a wireless material sensing system, according to some embodiments of the present disclosure.

FIG. 4 illustrates an exemplary block diagram of a second wireless device of a wireless material sensing system, according to some embodiments of the present disclosure.

FIG. 5 illustrates a flow chart of an exemplary method for wireless material sensing, according to some embodiments of the present disclosure.

FIG. 6 illustrates a flow chart of an exemplary method for CIR interpolation and CIR synchronization, according to some embodiments of the present disclosure.

FIG. 7 illustrates a flow chart of an exemplary method for CIR synchronization, according to some embodiments of the present disclosure.

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FIG. 8 illustrates a flow chart of another exemplary method for CIR synchronization, according to some embodiments of the present disclosure.

FIG. 9 illustrates a flow chart of an exemplary method for noise cancellation and target detection, according to some embodiments of the present disclosure.

FIG. 10 illustrates a flow chart of an exemplary method for obtaining background CIRs, according to some embodiments of the present disclosure.

FIG. 11 illustrates a flow chart of another exemplary method for obtaining background CIRs, according to some embodiments of the present disclosure.

FIG. 12 illustrates a flow chart of an exemplary method for material reflection feature (MRF) estimation, according to some embodiments of the present disclosure.

FIG. 13 illustrates a flow chart of another exemplary method for MRF estimation, according to some embodiments of the present disclosure.

FIG. 14 illustrates a flow chart of an exemplary method for wireless material sensing based on multiple frames, according to some embodiments of the present disclosure.

FIG. 15 illustrates a flow chart of an exemplary method for training a classifier during a training stage of a wireless material sensing system, according to some embodiments of the present disclosure.

FIG. 16 illustrates an exemplary set of material reflection features (MRFs) of several common materials, according to some embodiments of the present disclosure.

FIG. 17 illustrates exemplary CIR measurements with and without a target object in the field of interest, according to some embodiments of the present disclosure.

FIG. 18A illustrates an exemplary CIR interpolation, according to some embodiments of the present disclosure.

FIG. 18B illustrates an exemplary CIR amplitude after noise cancellation, according to some embodiments of the present disclosure.

FIGS. 19A-19C illustrate exemplary performances of a wireless material sensing system, according to some embodiments of the present disclosure.

## DETAILED DESCRIPTION

In one embodiment, the present teaching discloses a method, apparatus, device, system, and/or software (method/apparatus/device/system/software) of a wireless monitoring system. A time series of channel information (CI) of a wireless multipath channel (channel) may be obtained (e.g. dynamically) using a processor, a memory communicatively coupled with the processor and a set of instructions stored in the memory. The time series of CI (TSCI) may be extracted from a wireless signal (signal) transmitted between a Type 1 heterogeneous wireless device (e.g. wireless transmitter, Tx) and a Type 2 heterogeneous wireless device (e.g. wireless receiver, Rx) in a venue through the channel. The channel may be impacted by an expression (e.g. motion, movement, expression, and/or change in position/pose/shape/expression) of an object in the venue. A characteristics and/or a spatial-temporal information (STI, e.g. motion information) of the object and/or of the motion of the object may be monitored based on the TSCI. A task may be performed based on the characteristics and/or STI. A presentation associated with the task may be generated in a user-interface (UI) on a device of a user. The TSCI may be a wireless signal stream. The TSCI or each CI may be preprocessed. A device may be a station (STA). The symbol "A/B" means "A and/or B" in the present teaching.



The expression may comprise placement, placement of moveable parts, location, position, orientation, identifiable place, region, spatial coordinate, presentation, state, static expression, size, length, width, height, angle, scale, shape, curve, surface, area, volume, pose, posture, manifestation, body language, dynamic expression, motion, motion sequence, gesture, extension, contraction, distortion, deformation, body expression (e.g. head, face, eye, mouth, tongue, hair, voice, neck, limbs, arm, hand, leg, foot, muscle, moveable parts), surface expression (e.g. shape, texture, material, color, electromagnetic (EM) characteristics, visual pattern, wetness, reflectance, translucency, flexibility), material property (e.g. living tissue, hair, fabric, metal, wood, leather, plastic, artificial material, solid, liquid, gas, temperature), movement, activity, behavior, change of expression, and/or some combination.

The wireless signal may comprise: transmitted/received signal, EM radiation, RF signal/transmission, signal in licensed/unlicensed/ISM band, bandlimited signal, base-band signal, wireless/mobile/cellular communication signal, wireless/mobile/cellular network signal, mesh signal, light signal/communication, downlink/uplink signal, unicast/multicast/broadcast signal, standard (e.g. WLAN, WWAN, WPAN, WBAN, international, national, industry, defacto, IEEE, IEEE 802, 802.11/15/16, WiFi, 802.11n/ac/ax/be, 3G/4G/LTE/5G/6G/7G/8G, 3GPP, BLUETOOTH®, a trademark of BLUETOOTH SIG, INC. for telecommunication products and/or services (hereinafter “Bluetooth”), BLE, ZIGBEE®, a trademark of CONNECTIVITY STANDARDS ALLIANCE CORPORATION for telecommunication products and/or services (hereinafter “Zigbee”), RFID, UWB, WIMAX®, a trademark of WiMAX Forum CORPORATION for telecommunication products and/or services (hereinafter “WiMax”) compliant signal, protocol signal, standard frame, beacon/pilot/probe/enquiry/acknowledgement/handshake/synchronization signal, management/control/data frame, management/control/data signal, standardized wireless/cellular communication protocol, reference signal, source signal, motion probe/detection/sensing signal, and/or series of signals. The wireless signal may comprise a line-of-sight (LOS), and/or a non-LOS component (or path/link). Each CI may be extracted/generated/computed/sensed at a layer (e.g. PHY/MAC layer in OSI model) of Type 2 device and may be obtained by an application (e.g. software, firmware, driver, app, wireless monitoring software/system).

The wireless multipath channel may comprise: a communication channel, analog frequency channel (e.g. with analog carrier frequency near 700/800/900 MHz, 1.8/1.8/2.4/3/5/6/27/60 GHz), coded channel (e.g. in CDMA), and/or channel of a wireless network/system (e.g. WLAN, WiFi, mesh, LTE, 4G/5G, Bluetooth, Zigbee, UWB, RFID, microwave). It may comprise more than one channel. The channels may be consecutive (e.g. with adjacent/overlapping bands) or non-consecutive channels (e.g. non-overlapping WiFi channels, one at 2.4 GHz and one at 5 GHz).

The TSCI may be extracted from the wireless signal at a layer of the Type 2 device (e.g. a layer of OSI reference model, physical layer, data link layer, logical link control layer, media access control (MAC) layer, network layer, transport layer, session layer, presentation layer, application layer, TCP/IP layer, internet layer, link layer). The TSCI may be extracted from a derived signal (e.g. baseband signal, motion detection signal, motion sensing signal) derived from the wireless signal (e.g. RF signal). It may be (wireless) measurements sensed by the communication protocol (e.g. standardized protocol) using existing mechanism (e.g. wireless/cellular communication standard/network,

3G/LTE/4G/5G/6G/7G/8G, WiFi, IEEE 802.11/15/16). The derived signal may comprise a packet with at least one of: a preamble, a header and a payload (e.g. for data/control/management in wireless links/networks). The TSCI may be extracted from a probe signal (e.g. training sequence, STF, LTF, L-STF, L-LTF, L-SIG, HE-STF, HE-LTF, HE-SIG-A, HE-SIG-B, CEF) in the packet. A motion detection/sensing signal may be recognized/identified base on the probe signal. The packet may be a standard-compliant protocol frame, management frame, control frame, data frame, sounding frame, excitation frame, illumination frame, null data frame, beacon frame, pilot frame, probe frame, request frame, response frame, association frame, reassociation frame, disassociation frame, authentication frame, action frame, report frame, poll frame, announcement frame, extension frame, enquiry frame, acknowledgement frame, RTS frame, CTS frame, QoS frame, CF-Poll frame, CF-Ack frame, block acknowledgement frame, reference frame, training frame, and/or synchronization frame.

The packet may comprise a control data and/or a motion detection probe. A data (e.g. ID/parameters/characteristics/settings/control signal/command/instruction/notification/broadcasting-related information of the Type 1 device) may be obtained from the payload. The wireless signal may be transmitted by the Type 1 device. It may be received by the Type 2 device. A database (e.g. in local server, hub device, cloud server, storage network) may be used to store the TSCI, characteristics, STI, signatures, patterns, behaviors, trends, parameters, analytics, output responses, identification information, user information, device information, channel information, venue (e.g. map, environmental model, network, proximity devices/networks) information, task information, class/category information, presentation (e.g. UI) information, and/or other information.

The Type 1/Type 2 device may comprise at least one of: electronics, circuitry, transmitter (Tx)/receiver (Rx)/transceiver, RF interface, “Origin Satellite”/“Tracker Bot”, unicast/multicast/broadcasting device, wireless source device, source/destination device, wireless node, hub device, target device, motion detection device, sensor device, remote/wireless sensor device, wireless communication device, wireless-enabled device, standard compliant device, and/or receiver. The Type 1 (or Type 2) device may be heterogeneous because, when there are more than one instances of Type 1 (or Type 2) device, they may have different circuitry, enclosure, structure, purpose, auxiliary functionality, chip/IC, processor, memory, software, firmware, network connectivity, antenna, brand, model, appearance, form, shape, color, material, and/or specification. The Type 1/Type 2 device may comprise: access point, router, mesh router, internet-of-things (IoT) device, wireless terminal, one or more radio/RF subsystem/wireless interface (e.g. 2.4 GHz radio, 5 GHz radio, front haul radio, backhaul radio), modem, RF front end, RF/radio chip or integrated circuit (IC).

At least one of: Type 1 device, Type 2 device, a link between them, the object, the characteristics, the STI, the monitoring of the motion, and the task may be associated with an identification (ID) such as UUID. The Type 1/Type 2/another device may obtain/store/retrieve/access/preprocess/condition/process/analyze/monitor/apply the TSCI. The Type 1 and Type 2 devices may communicate network traffic in another channel (e.g. Ethernet, HDMI, USB, Bluetooth, BLE, WiFi, LTE, other network, the wireless multipath channel) in parallel to the wireless signal. The Type 2 device may passively observe/monitor/receive the wireless signal from the Type 1 device in the wireless multipath



channel without establishing connection (e.g. association/authentication) with, or requesting service from, the Type 1 device.

The transmitter (i.e. Type 1 device) may function as (play role of) receiver (i.e. Type 2 device) temporarily, sporadically, continuously, repeatedly, interchangeably, alternately, simultaneously, concurrently, and/or contemporaneously; and vice versa. A device may function as Type 1 device (transmitter) and/or Type 2 device (receiver) temporarily, sporadically, continuously, repeatedly, simultaneously, concurrently, and/or contemporaneously. There may be multiple wireless nodes each being Type 1 (Tx) and/or Type 2 (Rx) device. A TSCI may be obtained between every two nodes when they exchange/communicate wireless signals. The characteristics and/or STI of the object may be monitored individually based on a TSCI, or jointly based on two or more (e.g. all) TSCI.

The motion of the object may be monitored actively (in that Type 1 device, Type 2 device, or both, are wearable of/associated with the object) and/or passively (in that both Type 1 and Type 2 devices are not wearable of/associated with the object). It may be passive because the object may not be associated with the Type 1 device and/or the Type 2 device. The object (e.g. user, an automated guided vehicle or AGV) may not need to carry/install any wearables/fixtures (i.e. the Type 1 device and the Type 2 device are not wearable/attached devices that the object needs to carry in order perform the task). It may be active because the object may be associated with either the Type 1 device and/or the Type 2 device. The object may carry (or installed) a wearable/a fixture (e.g. the Type 1 device, the Type 2 device, a device communicatively coupled with either the Type 1 device or the Type 2 device).

The presentation may be visual, audio, image, video, animation, graphical presentation, text, etc. A computation of the task may be performed by a processor (or logic unit) of the Type 1 device, a processor (or logic unit) of an IC of the Type 1 device, a processor (or logic unit) of the Type 2 device, a processor of an IC of the Type 2 device, a local server, a cloud server, a data analysis subsystem, a signal analysis subsystem, and/or another processor. The task may be performed with/without reference to a wireless fingerprint or a baseline (e.g. collected, processed, computed, transmitted and/or stored in a training phase/survey/current survey/previous survey/recent survey/initial wireless survey, a passive fingerprint), a training, a profile, a trained profile, a static profile, a survey, an initial wireless survey, an initial setup, an installation, a re-training, an updating and a reset.

The Type 1 device (TX device) may comprise at least one heterogeneous wireless transmitter. The Type 2 device (RX device) may comprise at least one heterogeneous wireless receiver. The Type 1 device and the Type 2 device may be collocated. The Type 1 device and the Type 2 device may be the same device. Any device may have a data processing unit/apparatus, a computing unit/system, a network unit/system, a processor (e.g. logic unit), a memory communicatively coupled with the processor, and a set of instructions stored in the memory to be executed by the processor. Some processors, memories and sets of instructions may be coordinated.

There may be multiple Type 1 devices interacting (e.g. communicating, exchange signal/control/notification/other data) with the same Type 2 device (or multiple Type 2 devices), and/or there may be multiple Type 2 devices interacting with the same Type 1 device. The multiple Type 1 devices/Type 2 devices may be synchronized and/or asynchronous, with same/different window width/size and/

or time shift, same/different synchronized start time, synchronized end time, etc. Wireless signals sent by the multiple Type 1 devices may be sporadic, temporary, continuous, repeated, synchronous, simultaneous, concurrent, and/or contemporaneous. The multiple Type 1 devices/Type 2 devices may operate independently and/or collaboratively. A Type 1 and/or Type 2 device may have/comprise/be heterogeneous hardware circuitry (e.g. a heterogeneous chip or a heterogeneous IC capable of generating/receiving the wireless signal, extracting CI from received signal, or making the CI available). They may be communicatively coupled to same or different servers (e.g. cloud server, edge server, local server, hub device).

Operation of one device may be based on operation, state, internal state, storage, processor, memory output, physical location, computing resources, network of another device. Difference devices may communicate directly, and/or via another device/server/hub device/cloud server. The devices may be associated with one or more users, with associated settings. The settings may be chosen once, pre-programmed, and/or changed (e.g. adjusted, varied, modified)/varied over time. There may be additional steps in the method. The steps and/or the additional steps of the method may be performed in the order shown or in another order. Any steps may be performed in parallel, iterated, or otherwise repeated or performed in another manner. A user may be human, adult, older adult, man, woman, juvenile, child, baby, pet, animal, creature, machine, computer module/software, etc.

In the case of one or multiple Type 1 devices interacting with one or multiple Type 2 devices, any processing (e.g. time domain, frequency domain) may be different for different devices. The processing may be based on locations, orientation, direction, roles, user-related characteristics, settings, configurations, available resources, available bandwidth, network connection, hardware, software, processor, co-processor, memory, battery life, available power, antennas, antenna types, directional/unidirectional characteristics of the antenna, power setting, and/or other parameters/characteristics of the devices.

The wireless receiver (e.g. Type 2 device) may receive the signal and/or another signal from the wireless transmitter (e.g. Type 1 device). The wireless receiver may receive another signal from another wireless transmitter (e.g. a second Type 1 device). The wireless transmitter may transmit the signal and/or another signal to another wireless receiver (e.g. a second Type 2 device). The wireless transmitter, wireless receiver, another wireless receiver and/or another wireless transmitter may be moving with the object and/or another object. The another object may be tracked.

The Type 1 and/or Type 2 device may be capable of wirelessly coupling with at least two Type 2 and/or Type 1 devices. The Type 1 device may be caused/controlled to switch/establish wireless coupling (e.g. association, authentication) from the Type 2 device to a second Type 2 device at another location in the venue. Similarly, the Type 2 device may be caused/controlled to switch/establish wireless coupling from the Type 1 device to a second Type 1 device at yet another location in the venue. The switching may be controlled by a server (or a hub device), the processor, the Type 1 device, the Type 2 device, and/or another device. The radio used before and after switching may be different. A second wireless signal (second signal) may be caused to be transmitted between the Type 1 device and the second Type 2 device (or between the Type 2 device and the second Type 1 device) through the channel. A second TSCI of the channel extracted from the second signal may be obtained. The second signal may be the first signal. The characteristics,



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STI and/or another quantity of the object may be monitored based on the second TSCI. The Type 1 device and the Type 2 device may be the same. The characteristics, STI and/or another quantity with different time stamps may form a waveform. The waveform may be displayed in the presentation.

The wireless signal and/or another signal may have data embedded. The wireless signal may be a series of probe signals (e.g. a repeated transmission of probe signals, a re-use of one or more probe signals). The probe signals may change/vary over time. A probe signal may be a standard compliant signal, protocol signal, standardized wireless protocol signal, control signal, data signal, wireless communication network signal, cellular network signal, WiFi signal, LTE/5G/6G/7G signal, reference signal, beacon signal, motion detection signal, and/or motion sensing signal. A probe signal may be formatted according to a wireless network standard (e.g. WiFi), a cellular network standard (e.g. LTE/5G/6G), or another standard. A probe signal may comprise a packet with a header and a payload. A probe signal may have data embedded. The payload may comprise data. A probe signal may be replaced by a data signal. The probe signal may be embedded in a data signal. The wireless receiver, wireless transmitter, another wireless receiver and/or another wireless transmitter may be associated with at least one processor, memory communicatively coupled with respective processor, and/or respective set of instructions stored in the memory which when executed cause the processor to perform any and/or all steps needed to determine the STI (e.g. motion information), initial STI, initial time, direction, instantaneous location, instantaneous angle, and/or speed, of the object.

The processor, the memory and/or the set of instructions may be associated with the Type 1 device, one of the at least one Type 2 device, the object, a device associated with the object, another device associated with the venue, a cloud server, a hub device, and/or another server.

The Type 1 device may transmit the signal in a broadcasting manner to at least one Type 2 device(s) through the channel in the venue. The signal is transmitted without the Type 1 device establishing wireless connection (e.g. association, authentication) with any Type 2 device, and without any Type 2 device requesting services from the Type 1 device. The Type 1 device may transmit to a particular media access control (MAC) address common for more than one Type 2 devices. Each Type 2 device may adjust its MAC address to the particular MAC address. The particular MAC address may be associated with the venue. The association may be recorded in an association table of an Association Server (e.g. hub device). The venue may be identified by the Type 1 device, a Type 2 device and/or another device based on the particular MAC address, the series of probe signals, and/or the at least one TSCI extracted from the probe signals.

For example, a Type 2 device may be moved to a new location in the venue (e.g. from another venue). The Type 1 device may be newly set up in the venue such that the Type 1 and Type 2 devices are not aware of each other. During set up, the Type 1 device may be instructed/guided/caused/controlled (e.g. using dummy receiver, using hardware pin setting/connection, using stored setting, using local setting, using remote setting, using downloaded setting, using hub device, or using server) to send the series of probe signals to the particular MAC address. Upon power up, the Type 2 device may scan for probe signals according to a table of MAC addresses (e.g. stored in a designated source, server, hub device, cloud server) that may be used for broadcasting

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at different locations (e.g. different MAC address used for different venue such as house, office, enclosure, floor, multi-storey building, store, airport, mall, stadium, hall, station, subway, lot, area, zone, region, district, city, country, continent). When the Type 2 device detects the probe signals sent to the particular MAC address, the Type 2 device can use the table to identify the venue based on the MAC address.

A location of a Type 2 device in the venue may be computed based on the particular MAC address, the series of probe signals, and/or the at least one TSCI obtained by the Type 2 device from the probe signals. The computing may be performed by the Type 2 device.

The particular MAC address may be changed (e.g. adjusted, varied, modified) over time. It may be changed according to a time table, rule, policy, mode, condition, situation and/or change. The particular MAC address may be selected based on availability of the MAC address, a pre-selected list, collision pattern, traffic pattern, data traffic between the Type 1 device and another device, effective bandwidth, random selection, and/or a MAC address switching plan. The particular MAC address may be the MAC address of a second wireless device (e.g. a dummy receiver, or a receiver that serves as a dummy receiver).

The Type 1 device may transmit the probe signals in a channel selected from a set of channels. At least one CI of the selected channel may be obtained by a respective Type 2 device from the probe signal transmitted in the selected channel.

The selected channel may be changed (e.g. adjusted, varied, modified) over time. The change may be according to a time table, rule, policy, mode, condition, situation, and/or change. The selected channel may be selected based on availability of channels, random selection, a pre-selected list, co-channel interference, inter-channel interference, channel traffic pattern, data traffic between the Type 1 device and another device, effective bandwidth associated with channels, security criterion, channel switching plan, a criterion, a quality criterion, a signal quality condition, and/or consideration.

The particular MAC address and/or an information of the selected channel may be communicated between the Type 1 device and a server (e.g. hub device) through a network. The particular MAC address and/or the information of the selected channel may also be communicated between a Type 2 device and a server (e.g. hub device) through another network. The Type 2 device may communicate the particular MAC address and/or the information of the selected channel to another Type 2 device (e.g. via mesh network, Bluetooth, WiFi, NFC, ZigBee, etc.). The particular MAC address and/or selected channel may be chosen by a server (e.g. hub device). The particular MAC address and/or selected channel may be signaled in an announcement channel by the Type 1 device, the Type 2 device and/or a server (e.g. hub device). Before being communicated, any information may be pre-processed.

Wireless connection (e.g. association, authentication) between the Type 1 device and another wireless device may be established (e.g. using a signal handshake). The Type 1 device may send a first handshake signal (e.g. sounding frame, probe signal, request-to-send RTS) to the another device. The another device may reply by sending a second handshake signal (e.g. a command, or a clear-to-send CTS) to the Type 1 device, triggering the Type 1 device to transmit the signal (e.g. series of probe signals) in the broadcasting manner to multiple Type 2 devices without establishing connection with any Type 2 device. The second handshake



signals may be a response or an acknowledge (e.g. ACK) to the first handshake signal. The second handshake signal may contain a data with information of the venue, and/or the Type 1 device. The another device may be a dummy device with a purpose (e.g. primary purpose, secondary purpose) to establish the wireless connection with the Type 1 device, to receive the first signal, and/or to send the second signal. The another device may be physically attached to the Type 1 device.

In another example, the another device may send a third handshake signal to the Type 1 device triggering the Type 1 device to broadcast the signal (e.g. series of probe signals) to multiple Type 2 devices without establishing connection (e.g. association, authentication) with any Type 2 device. The Type 1 device may reply to the third special signal by transmitting a fourth handshake signal to the another device. The another device may be used to trigger more than one Type 1 devices to broadcast. The triggering may be sequential, partially sequential, partially parallel, or fully parallel. The another device may have more than one wireless circuitries to trigger multiple transmitters in parallel. Parallel trigger may also be achieved using at least one yet another device to perform the triggering (similar to what as the another device does) in parallel to the another device. The another device may not communicate (or suspend communication) with the Type 1 device after establishing connection with the Type 1 device. Suspended communication may be resumed. The another device may enter an inactive mode, hibernation mode, sleep mode, stand-by mode, low-power mode, OFF mode and/or power-down mode, after establishing the connection with the Type 1 device. The another device may have the particular MAC address so that the Type 1 device sends the signal to the particular MAC address. The Type 1 device and/or the another device may be controlled and/or coordinated by a first processor associated with the Type 1 device, a second processor associated with the another device, a third processor associated with a designated source and/or a fourth processor associated with another device. The first and second processors may coordinate with each other.

A first series of probe signals may be transmitted by a first antenna of the Type 1 device to at least one first Type 2 device through a first channel in a first venue. A second series of probe signals may be transmitted by a second antenna of the Type 1 device to at least one second Type 2 device through a second channel in a second venue. The first series and the second series may/may not be different. The at least one first Type 2 device may/may not be different from the at least one second Type 2 device. The first and/or second series of probe signals may be broadcasted without connection (e.g. association, authentication) established between the Type 1 device and any Type 2 device. The first and second antennas may be same/different.

The two venues may have different sizes, shape, multipath characteristics. The first and second venues may overlap. The respective immediate areas around the first and second antennas may overlap. The first and second channels may be same/different. For example, the first one may be WiFi while the second may be LTE. Or, both may be WiFi, but the first one may be 2.4 GHz WiFi and the second may be 5 GHz WiFi. Or, both may be 2.4 GHz WiFi, but have different channel numbers, SSID names, and/or WiFi settings.

Each Type 2 device may obtain at least one TSCI from the respective series of probe signals, the CI being of the respective channel between the Type 2 device and the Type 1 device. Some first Type 2 device(s) and some second Type 2 device(s) may be the same. The first and second series of

probe signals may be synchronous/asynchronous. A probe signal may be transmitted with data or replaced by a data signal. The first and second antennas may be the same.

The first series of probe signals may be transmitted at a first rate (e.g. 30 Hz). The second series of probe signals may be transmitted at a second rate (e.g. 200 Hz). The first and second rates may be same/different. The first and/or second rate may be changed (e.g. adjusted, varied, modified) over time. The change may be according to a time table, rule, policy, mode, condition, situation, and/or change. Any rate may be changed (e.g. adjusted, varied, modified) over time.

The first and/or second series of probe signals may be transmitted to a first MAC address and/or second MAC address respectively. The two MAC addresses may be same/different. The first series of probe signals may be transmitted in a first channel. The second series of probe signals may be transmitted in a second channel. The two channels may be same/different. The first or second MAC address, first or second channel may be changed over time. Any change may be according to a time table, rule, policy, mode, condition, situation, and/or change.

The Type 1 device and another device may be controlled and/or coordinated, physically attached, or may be off/in/of a common device. They may be controlled by/connected to a common data processor, or may be connected to a common bus interconnect/network/LAN/Bluetooth network/NFC network/BLE network/wired network/wireless network/mesh network/mobile network/cloud. They may share a common memory, or be associated with a common user, user device, profile, account, identity (ID), identifier, household, house, physical address, location, geographic coordinate, IP subnet, SSID, home device, office device, and/or manufacturing device.

Each Type 1 device may be a signal source of a set of respective Type 2 devices (i.e. it sends a respective signal (e.g. respective series of probe signals) to the set of respective Type 2 devices). Each respective Type 2 device chooses the Type 1 device from among all Type 1 devices as its signal source. Each Type 2 device may choose asynchronously. At least one TSCI may be obtained by each respective Type 2 device from the respective series of probe signals from the Type 1 device, the CI being of the channel between the Type 2 device and the Type 1 device.

The respective Type 2 device chooses the Type 1 device from among all Type 1 devices as its signal source based on identity (ID) or identifier of Type 1/Type 2 device, task to be performed, past signal source, history (e.g. of past signal source, Type 1 device, another Type 1 device, respective Type 2 receiver, and/or another Type 2 receiver), threshold for switching signal source, and/or information of a user, account, access info, parameter, characteristics, and/or signal strength (e.g. associated with the Type 1 device and/or the respective Type 2 receiver).

Initially, the Type 1 device may be signal source of a set of initial respective Type 2 devices (i.e. the Type 1 device sends a respective signal (series of probe signals) to the set of initial respective Type 2 devices) at an initial time. Each initial respective Type 2 device chooses the Type 1 device from among all Type 1 devices as its signal source.

The signal source (Type 1 device) of a particular Type 2 device may be changed (e.g. adjusted, varied, modified) when (1) time interval between two adjacent probe signals (e.g. between current probe signal and immediate past probe signal, or between next probe signal and current probe signal) received from current signal source of the Type 2 device exceeds a first threshold; (2) signal strength associated with current signal source of the Type 2 device is below



a second threshold; (3) a processed signal strength associated with current signal source of the Type 2 device is below a third threshold, the signal strength processed with low pass filter, band pass filter, median filter, moving average filter, weighted averaging filter, linear filter and/or non-linear filter; and/or (4) signal strength (or processed signal strength) associated with current signal source of the Type 2 device is below a fourth threshold for a significant percentage of a recent time window (e.g. 70%, 80%, 90%). The percentage may exceed a fifth threshold. The first, second, third, fourth and/or fifth thresholds may be time varying.

Condition (1) may occur when the Type 1 device and the Type 2 device become progressively far away from each other, such that some probe signal from the Type 1 device becomes too weak and is not received by the Type 2 device. Conditions (2)-(4) may occur when the two devices become far from each other such that the signal strength becomes very weak.

The signal source of the Type 2 device may not change if other Type 1 devices have signal strength weaker than a factor (e.g. 1, 1.1, 1.2, or 1.5) of the current signal source.

If the signal source is changed (e.g. adjusted, varied, modified), the new signal source may take effect at a near future time (e.g. the respective next time). The new signal source may be the Type 1 device with strongest signal strength, and/or processed signal strength. The current and new signal source may be same/different.

A list of available Type 1 devices may be initialized and maintained by each Type 2 device. The list may be updated by examining signal strength and/or processed signal strength associated with the respective set of Type 1 devices. A Type 2 device may choose between a first series of probe signals from a first Type 1 device and a second series of probe signals from a second Type 1 device based on: respective probe signal rate, MAC addresses, channels, characteristics/properties/states, task to be performed by the Type 2 device, signal strength of first and second series, and/or another consideration.

The series of probe signals may be transmitted at a regular rate (e.g. 100 Hz). The series of probe signals may be scheduled at a regular interval (e.g. 0.01 s for 100 Hz), but each probe signal may experience small time perturbation, perhaps due to timing requirement, timing control, network control, handshaking, message passing, collision avoidance, carrier sensing, congestion, availability of resources, and/or another consideration.

The rate may be changed (e.g. adjusted, varied, modified). The change may be according to a time table (e.g. changed once every hour), rule, policy, mode, condition and/or change (e.g. changed whenever some event occur). For example, the rate may normally be 100 Hz, but changed to 1000 Hz in demanding situations, and to 1 Hz in low power/standby situation. The probe signals may be sent in burst.

The probe signal rate may change based on a task performed by the Type 1 device or Type 2 device (e.g. a task may need 100 Hz normally and 1000 Hz momentarily for 20 seconds). In one example, the transmitters (Type 1 devices), receivers (Type 2 device), and associated tasks may be associated adaptively (and/or dynamically) to classes (e.g. classes that are: low-priority, high-priority, emergency, critical, regular, privileged, non-subscription, subscription, paying, and/or non-paying). A rate (of a transmitter) may be adjusted for the sake of some class (e.g. high priority class). When the need of that class changes, the rate may be changed (e.g. adjusted, varied, modified). When a receiver has critically low power, the rate may be reduced to reduce

power consumption of the receiver to respond to the probe signals. In one example, probe signals may be used to transfer power wirelessly to a receiver (Type 2 device), and the rate may be adjusted to control the amount of power transferred to the receiver.

The rate may be changed by (or based on): a server (e.g. hub device), the Type 1 device and/or the Type 2 device. Control signals may be communicated between them. The server may monitor, track, forecast and/or anticipate the needs of the Type 2 device and/or the tasks performed by the Type 2 device, and may control the Type 1 device to change the rate. The server may make scheduled changes to the rate according to a time table. The server may detect an emergency situation and change the rate immediately. The server may detect a developing condition and adjust the rate gradually.

The characteristics and/or STI (e.g. motion information) may be monitored individually based on a TSCI associated with a particular Type 1 device and a particular Type 2 device, and/or monitored jointly based on any TSCI associated with the particular Type 1 device and any Type 2 device, and/or monitored jointly based on any TSCI associated with the particular Type 2 device and any Type 1 device, and/or monitored globally based on any TSCI associated with any Type 1 device and any Type 2 device. Any joint monitoring may be associated with: a user, user account, profile, household, map of venue, environmental model of the venue, and/or user history, etc.

A first channel between a Type 1 device and a Type 2 device may be different from a second channel between another Type 1 device and another Type 2 device. The two channels may be associated with different frequency bands, bandwidth, carrier frequency, modulation, wireless standards, coding, encryption, payload characteristics, networks, network ID, SSID, network characteristics, network settings, and/or network parameters, etc.

The two channels may be associated with different kinds of wireless system (e.g. two of the following: WiFi, LTE, LTE-A, LTE-U, 2.5G, 3G, 3.5G, 4G, beyond 4G, 5G, 6G, 7G, a cellular network standard, UMTS, 3GPP, GSM, EDGE, TDMA, FDMA, CDMA, WCDMA, TD-SCDMA, 802.11 system, 802.15 system, 802.16 system, mesh network, Zigbee, NFC, WiMax, Bluetooth, BLE, RFID, UWB, microwave system, radar like system). For example, one is WiFi and the other is LTE.

The two channels may be associated with similar kinds of wireless system, but in different network. For example, the first channel may be associated with a WiFi network named "Pizza and Pizza" in the 2.4 GHz band with a bandwidth of 20 MHz while the second may be associated with a WiFi network with SSID of "StarBud hotspot" in the 5 GHz band with a bandwidth of 40 MHz. The two channels may be different channels in same network (e.g. the "StarBud hotspot" network).

In one embodiment, a wireless monitoring system may comprise training a classifier of multiple events in a venue based on training TSCI associated with the multiple events. A CI or TSCI associated with an event may be considered/may comprise a wireless sample/characteristics/fingerprint associated with the event (and/or the venue, the environment, the object, the motion of the object, a state/emotional state/mental state/condition/stage/gesture/gait/action/movement/activity/daily activity/history/event of the object, etc.).

For each of the multiple known events happening in the venue in a respective training (e.g. surveying, wireless survey, initial wireless survey) time period associated with the known event, a respective training wireless signal (e.g.



a respective series of training probe signals) may be transmitted by an antenna of a first Type 1 heterogeneous wireless device using a processor, a memory and a set of instructions of the first Type 1 device to at least one first Type 2 heterogeneous wireless device through a wireless multipath channel in the venue in the respective training time period.

At least one respective time series of training CI (training TSCI) may be obtained asynchronously by each of the at least one first Type 2 device from the (respective) training signal. The CI may be CI of the channel between the first Type 2 device and the first Type 1 device in the training time period associated with the known event. The at least one training TSCI may be preprocessed. The training may be a wireless survey (e.g. during installation of Type 1 device and/or Type 2 device).

For a current event happening in the venue in a current time period, a current wireless signal (e.g. a series of current probe signals) may be transmitted by an antenna of a second Type 1 heterogeneous wireless device using a processor, a memory and a set of instructions of the second Type 1 device to at least one second Type 2 heterogeneous wireless device through the channel in the venue in the current time period associated with the current event.

At least one time series of current CI (current TSCI) may be obtained asynchronously by each of the at least one second Type 2 device from the current signal (e.g. the series of current probe signals). The CI may be CI of the channel between the second Type 2 device and the second Type 1 device in the current time period associated with the current event. The at least one current TSCI may be preprocessed.

The classifier may be applied to classify at least one current TSCI obtained from the series of current probe signals by the at least one second Type 2 device, to classify at least one portion of a particular current TSCI, and/or to classify a combination of the at least one portion of the particular current TSCI and another portion of another TSCI. The classifier may partition TSCI (or the characteristics/STI or other analytics or output responses) into clusters and associate the clusters to specific events/objects/subjects/locations/movements/activities. Labels/tags may be generated for the clusters. The clusters may be stored and retrieved. The classifier may be applied to associate the current TSCI (or characteristics/STI or the other analytics/output response, perhaps associated with a current event) with: a cluster, a known/specific event, a class/category/group/grouping/list/cluster/set of known events/subjects/locations/movements/activities, an unknown event, a class/category/group/grouping/list/cluster/set of unknown events/subjects/locations/movements/activities, and/or another event/subject/location/movement/activity/class/category/group/grouping/list/cluster/set. Each TSCI may comprise at least one CI each associated with a respective timestamp. Two TSCI associated with two Type 2 devices may be different with different: starting time, duration, stopping time, amount of CI, sampling frequency, sampling period. Their CI may have different features. The first and second Type 1 devices may be at same location in the venue. They may be the same device. The at least one second Type 2 device (or their locations) may be a permutation of the at least one first Type 2 device (or their locations). A particular second Type 2 device and a particular first Type 2 device may be the same device.

A subset of the first Type 2 device and a subset of the second Type 2 device may be the same. The at least one second Type 2 device and/or a subset of the at least one second Type 2 device may be a subset of the at least one first Type 2 device. The at least one first Type 2 device and/or a

subset of the at least one first Type 2 device may be a permutation of a subset of the at least one second Type 2 device. The at least one second Type 2 device and/or a subset of the at least one second Type 2 device may be a permutation of a subset of the at least one first Type 2 device. The at least one second Type 2 device and/or a subset of the at least one second Type 2 device may be at same respective location as a subset of the at least one first Type 2 device. The at least one first Type 2 device and/or a subset of the at least one first Type 2 device may be at same respective location as a subset of the at least one second Type 2 device.

The antenna of the Type 1 device and the antenna of the second Type 1 device may be at same location in the venue. Antenna(s) of the at least one second Type 2 device and/or antenna(s) of a subset of the at least one second Type 2 device may be at same respective location as respective antenna(s) of a subset of the at least one first Type 2 device. Antenna(s) of the at least one first Type 2 device and/or antenna(s) of a subset of the at least one first Type 2 device may be at same respective location(s) as respective antenna(s) of a subset of the at least one second Type 2 device.

A first section of a first time duration of the first TSCI and a second section of a second time duration of the second section of the second TSCI may be aligned. A map between items of the first section and items of the second section may be computed. The first section may comprise a first segment (e.g. subset) of the first TSCI with a first starting/ending time, and/or another segment (e.g. subset) of a processed first TSCI. The processed first TSCI may be the first TSCI processed by a first operation. The second section may comprise a second segment (e.g. subset) of the second TSCI with a second starting time and a second ending time, and another segment (e.g. subset) of a processed second TSCI. The processed second TSCI may be the second TSCI processed by a second operation. The first operation and/or the second operation may comprise: subsampling, re-sampling, interpolation, filtering, transformation, feature extraction, pre-processing, and/or another operation.

A first item of the first section may be mapped to a second item of the second section. The first item of the first section may also be mapped to another item of the second section. Another item of the first section may also be mapped to the second item of the second section. The mapping may be one-to-one, one-to-many, many-to-one, many-to-many. At least one function of at least one of: the first item of the first section of the first TSCI, another item of the first TSCI, timestamp of the first item, time difference of the first item, time differential of the first item, neighboring timestamp of the first item, another timestamp associated with the first item, the second item of the second section of the second TSCI, another item of the second TSCI, timestamp of the second item, time difference of the second item, time differential of the second item, neighboring timestamp of the second item, and another timestamp associated with the second item, may satisfy at least one constraint.

One constraint may be that a difference between the timestamp of the first item and the timestamp of the second item may be upper-bounded by an adaptive (and/or dynamically adjusted) upper threshold and lower-bounded by an adaptive lower threshold.

The first section may be the entire first TSCI. The second section may be the entire second TSCI. The first time duration may be equal to the second time duration. A section of a time duration of a TSCI may be determined adaptively (and/or dynamically). A tentative section of the TSCI may be computed. A starting time and an ending time of a section



(e.g. the tentative section, the section) may be determined. The section may be determined by removing a beginning portion and an ending portion of the tentative section. A beginning portion of a tentative section may be determined as follows. Iteratively, items of the tentative section with increasing timestamp may be considered as a current item, one item at a time.

In each iteration, at least one activity measure/index may be computed and/or considered. The at least one activity measure may be associated with at least one of: the current item associated with a current timestamp, past items of the tentative section with timestamps not larger than the current timestamp, and/or future items of the tentative section with timestamps not smaller than the current timestamp. The current item may be added to the beginning portion of the tentative section if at least one criterion (e.g. quality criterion, signal quality condition) associated with the at least one activity measure is satisfied.

The at least one criterion associated with the activity measure may comprise at least one of: (a) the activity measure is smaller than an adaptive (e.g. dynamically adjusted) upper threshold, (b) the activity measure is larger than an adaptive lower threshold, (c) the activity measure is smaller than an adaptive upper threshold consecutively for at least a predetermined amount of consecutive timestamps, (d) the activity measure is larger than an adaptive lower threshold consecutively for at least another predetermined amount of consecutive timestamps, (e) the activity measure is smaller than an adaptive upper threshold consecutively for at least a predetermined percentage of the predetermined amount of consecutive timestamps, (f) the activity measure is larger than an adaptive lower threshold consecutively for at least another predetermined percentage of the another predetermined amount of consecutive timestamps, (g) another activity measure associated with another timestamp associated with the current timestamp is smaller than another adaptive upper threshold and larger than another adaptive lower threshold, (h) at least one activity measure associated with at least one respective timestamp associated with the current timestamp is smaller than respective upper threshold and larger than respective lower threshold, (i) percentage of timestamps with associated activity measure smaller than respective upper threshold and larger than respective lower threshold in a set of timestamps associated with the current timestamp exceeds a threshold, and (j) another criterion (e.g. a quality criterion, signal quality condition).

An activity measure/index associated with an item at time T1 may comprise at least one of: (1) a first function of the item at time T1 and an item at time T1-D1, wherein D1 is a pre-determined positive quantity (e.g. a constant time offset), (2) a second function of the item at time T1 and an item at time T1+D1, (3) a third function of the item at time T1 and an item at time T2, wherein T2 is a pre-determined quantity (e.g. a fixed initial reference time; T2 may be changed (e.g. adjusted, varied, modified) over time; T2 may be updated periodically; T2 may be the beginning of a time period and T1 may be a sliding time in the time period), and (4) a fourth function of the item at time T1 and another item.

At least one of: the first function, the second function, the third function, and/or the fourth function may be a function (e.g.  $F(X, Y, \dots)$ ) with at least two arguments: X and Y. The two arguments may be scalars. The function (e.g. F) may be a function of at least one of: X, Y,  $(X-Y)$ ,  $(Y-X)$ ,  $\text{abs}(X-Y)$ ,  $X^a$ ,  $Y^b$ ,  $\text{abs}(X^a-Y^b)$ ,  $(X-Y)^a$ ,  $(X/Y)$ ,  $(X+a)/(Y+b)$ ,  $(X^a/Y^b)$ , and  $((X/Y)^a-b)$ , wherein a and b are may be some predetermined quantities. For example, the function

may simply be  $\text{abs}(X-Y)$ , or  $(X-Y)^2$ ,  $(X-Y)^4$ . The function may be a robust function. For example, the function may be  $(X-Y)^2$  when  $\text{abs}(X-Y)$  is less than a threshold T, and  $(X-Y)+a$  when  $\text{abs}(X-Y)$  is larger than T. Alternatively, the function may be a constant when  $\text{abs}(X-Y)$  is larger than T. The function may also be bounded by a slowly increasing function when  $\text{abs}(X-y)$  is larger than T, so that outliers cannot severely affect the result. Another example of the function may be  $(\text{abs}(X/Y)-a)$ , where  $a=1$ . In this way, if  $X=Y$  (i.e. no change or no activity), the function will give a value of 0. If X is larger than Y,  $(X/Y)$  will be larger than 1 (assuming X and Y are positive) and the function will be positive. And if X is less than Y,  $(X/Y)$  will be smaller than 1 and the function will be negative. In another example, both arguments X and Y may be n-tuples such that  $X=(x_1, x_2, \dots, x_n)$  and  $Y=(y_1, y_2, \dots, y_n)$ . The function may be a function of at least one of:  $x_i$ ,  $y_i$ ,  $(x_i-y_i)$ ,  $(y_i-x_i)$ ,  $\text{abs}(x_i-y_i)$ ,  $x_i^a$ ,  $y_i^b$ ,  $\text{abs}(x_i^a-y_i^b)$ ,  $(x_i-y_i)^a$ ,  $(x_i/y_i)$ ,  $(x_i+a)/(y_i+b)$ ,  $(x_i^a/y_i^b)$ , and  $((x_i/y_i)^a-b)$ , wherein i is a component index of the n-tuple X and Y, and  $1 \leq i \leq n$ , e.g. component index of  $x_1$  is  $i=1$ , component index of  $x_2$  is  $i=2$ . The function may comprise a component-by-component summation of another function of at least one of the following:  $x_i$ ,  $y_i$ ,  $(x_i-y_i)$ ,  $(y_i-x_i)$ ,  $\text{abs}(x_i-y_i)$ ,  $x_i^a$ ,  $y_i^b$ ,  $\text{abs}(x_i^a-y_i^b)$ ,  $(x_i-y_i)^a$ ,  $(x_i/y_i)$ ,  $(x_i+a)/(y_i+b)$ ,  $(x_i^a/y_i^b)$ , and  $((x_i/y_i)^a-b)$ , wherein i is the component index of the n-tuple X and Y. For example, the function may be in a form of  $\sum_{i=1}^n (\text{abs}(x_i/y_i)-1)/n$ , or  $\sum_{i=1}^n w_i * (\text{abs}(x_i/y_i)-1)$ , where  $w_i$  is some weight for component i.

The map may be computed using dynamic time warping (DTW). The DTW may comprise a constraint on at least one of: the map, the items of the first TSCI, the items of the second TSCI, the first time duration, the second time duration, the first section, and/or the second section. Suppose in the map, the  $i^{\text{th}}$  domain item is mapped to the  $j^{\text{th}}$  range item. The constraint may be on admissible combination of i and j (constraint on relationship between i and j). Mismatch cost between a first section of a first time duration of a first TSCI and a second section of a second time duration of a second TSCI may be computed.

The first section and the second section may be aligned such that a map comprising more than one links may be established between first items of the first TSCI and second items of the second TSCI. With each link, one of the first items with a first timestamp may be associated with one of the second items with a second timestamp. A mismatch cost between the aligned first section and the aligned second section may be computed. The mismatch cost may comprise a function of: an item-wise cost between a first item and a second item associated by a particular link of the map, and a link-wise cost associated with the particular link of the map.

The aligned first section and the aligned second section may be represented respectively as a first vector and a second vector of same vector length. The mismatch cost may comprise at least one of: an inner product, inner-product-like quantity, quantity based on correlation, correlation indicator, quantity based on covariance, discriminating score, distance, Euclidean distance, absolute distance, Lk distance (e.g. L1, L2,  $\dots$ ), weighted distance, distance-like quantity and/or another similarity value, between the first vector and the second vector. The mismatch cost may be normalized by the respective vector length.

A parameter derived from the mismatch cost between the first section of the first time duration of the first TSCI and the



second section of the second time duration of the second TSCI may be modeled with a statistical distribution. At least one of: a scale parameter, location parameter and/or another parameter, of the statistical distribution may be estimated.

The first section of the first time duration of the first TSCI may be a sliding section of the first TSCI. The second section of the second time duration of the second TSCI may be a sliding section of the second TSCI.

A first sliding window may be applied to the first TSCI and a corresponding second sliding window may be applied to the second TSCI. The first sliding window of the first TSCI and the corresponding second sliding window of the second TSCI may be aligned.

Mismatch cost between the aligned first sliding window of the first TSCI and the corresponding aligned second sliding window of the second TSCI may be computed. The current event may be associated with at least one of: the known event, the unknown event and/or the another event, based on the mismatch cost.

The classifier may be applied to at least one of: each first section of the first time duration of the first TSCI, and/or each second section of the second time duration of the second TSCI, to obtain at least one tentative classification results. Each tentative classification result may be associated with a respective first section and a respective second section.

The current event may be associated with at least one of: the known event, the unknown event, a class/category/group/grouping/list/set of unknown events, and/or the another event, based on the mismatch cost. The current event may be associated with at least one of: the known event, the unknown event and/or the another event, based on a largest number of tentative classification results in more than one sections of the first TSCI and corresponding more than sections of the second TSCI. For example, the current event may be associated with a particular known event if the mismatch cost points to the particular known event for N consecutive times (e.g. N=10). In another example, the current event may be associated with a particular known event if the percentage of mismatch cost within the immediate past N consecutive N pointing to the particular known event exceeds a certain threshold (e.g. >80%).

In another example, the current event may be associated with a known event that achieves smallest mismatch cost for the most times within a time period. The current event may be associated with a known event that achieves smallest overall mismatch cost, which is a weighted average of at least one mismatch cost associated with the at least one first sections. The current event may be associated with a particular known event that achieves smallest of another overall cost. The current event may be associated with the "unknown event" if none of the known events achieve mismatch cost lower than a first threshold T1 in a sufficient percentage of the at least one first section. The current event may also be associated with the "unknown event" if none of the events achieve an overall mismatch cost lower than a second threshold T2. The current event may be associated with at least one of: the known event, the unknown event and/or the another event, based on the mismatch cost and additional mismatch cost associated with at least one additional section of the first TSCI and at least one additional section of the second TSCI. The known events may comprise at least one of: a door closed event, door open event, window closed event, window open event, multi-state event, on-state event, off-state event, intermediate state event, continuous state event, discrete state event, human-present

event, human-absent event, sign-of-life-present event, and/or a sign-of-life-absent event.

A projection for each CI may be trained using a dimension reduction method based on the training TSCI. The dimension reduction method may comprise at least one of: principal component analysis (PCA), PCA with different kernel, independent component analysis (ICA), Fisher linear discriminant, vector quantization, supervised learning, unsupervised learning, self-organizing maps, auto-encoder, neural network, deep neural network, and/or another method. The projection may be applied to at least one of: the training TSCI associated with the at least one event, and/or the current TSCI, for the classifier.

The classifier of the at least one event may be trained based on the projection and the training TSCI associated with the at least one event. The at least one current TSCI may be classified/categorized based on the projection and the current TSCI. The projection may be re-trained using at least one of: the dimension reduction method, and another dimension reduction method, based on at least one of: the training TSCI, at least one current TSCI before retraining the projection, and/or additional training TSCI. The another dimension reduction method may comprise at least one of: principal component analysis (PCA), PCA with different kernels, independent component analysis (ICA), Fisher linear discriminant, vector quantization, supervised learning, unsupervised learning, self-organizing maps, auto-encoder, neural network, deep neural network, and/or yet another method. The classifier of the at least one event may be re-trained based on at least one of: the re-trained projection, the training TSCI associated with the at least one events, and/or at least one current TSCI. The at least one current TSCI may be classified based on: the re-trained projection, the re-trained classifier, and/or the current TSCI.

Each CI may comprise a vector of complex values. Each complex value may be preprocessed to give the magnitude of the complex value. Each CI may be preprocessed to give a vector of non-negative real numbers comprising the magnitude of corresponding complex values. Each training TSCI may be weighted in the training of the projection. The projection may comprise more than one projected components. The projection may comprise at least one most significant projected component. The projection may comprise at least one projected component that may be beneficial for the classifier.

Channel/Channel Information/Venue/Spatial-Temporal Info/Motion/Object

The channel information (CI) may be associated with/may comprise signal strength, signal amplitude, signal phase, spectral power measurement, modem parameters (e.g. used in relation to modulation/demodulation in digital communication systems such as WiFi, 4G/LTE), dynamic beamforming information, transfer function components, radio state (e.g. used in digital communication systems to decode digital data, baseband processing state, RF processing state, etc.), measurable variables, sensed data, coarse-grained/fine-grained information of a layer (e.g. physical layer, data link layer, MAC layer, etc.), digital setting, gain setting, RF filter setting, RF front end switch setting, DC offset setting, DC correction setting, IQ compensation setting, effect(s) on the wireless signal by the environment (e.g. venue) during propagation, transformation of an input signal (the wireless signal transmitted by the Type 1 device) to an output signal (the wireless signal received by the Type 2 device), a stable behavior of the environment, a state profile, wireless channel measurements, received signal strength indicator (RSSI), channel state information (CSI), channel impulse response



(CIR), channel frequency response (CFR), characteristics of frequency components (e.g. subcarriers) in a bandwidth, channel characteristics, channel filter response, timestamp, auxiliary information, data, meta data, user data, account data, access data, security data, session data, status data, supervisory data, household data, identity (ID), identifier, device data, network data, neighborhood data, environment data, real-time data, sensor data, stored data, encrypted data, compressed data, protected data, and/or another channel information. Each CI may be associated with a time stamp, and/or an arrival time. A CSI can be used to equalize/undo/minimize/reduce the multipath channel effect (of the transmission channel) to demodulate a signal similar to the one transmitted by the transmitter through the multipath channel. The CI may be associated with information associated with a frequency band, frequency signature, frequency phase, frequency amplitude, frequency trend, frequency characteristics, frequency-like characteristics, time domain element, frequency domain element, time-frequency domain element, orthogonal decomposition characteristics, and/or non-orthogonal decomposition characteristics of the signal through the channel. The TSCI may be a stream of wireless signals (e.g. CI).

The CI may be preprocessed, processed, postprocessed, stored (e.g. in local memory, portable/mobile memory, removable memory, storage network, cloud memory, in a volatile manner, in a non-volatile manner), retrieved, transmitted and/or received. One or more modem parameters and/or radio state parameters may be held constant. The modem parameters may be applied to a radio subsystem. The modem parameters may represent a radio state. A motion detection signal (e.g. baseband signal, and/or packet decoded/demodulated from the baseband signal, etc.) may be obtained by processing (e.g. down-converting) the first wireless signal (e.g. RF/WiFi/LTE/5G signal) by the radio subsystem using the radio state represented by the stored modem parameters. The modem parameters/radio state may be updated (e.g. using previous modem parameters or previous radio state). Both the previous and updated modem parameters/radio states may be applied in the radio subsystem in the digital communication system. Both the previous and updated modem parameters/radio states may be compared/analyzed/processed/monitored in the task.

The channel information may also be modem parameters (e.g. stored or freshly computed) used to process the wireless signal. The wireless signal may comprise a plurality of probe signals. The same modem parameters may be used to process more than one probe signals. The same modem parameters may also be used to process more than one wireless signals. The modem parameters may comprise parameters that indicate settings or an overall configuration for the operation of a radio subsystem or a baseband subsystem of a wireless sensor device (or both). The modem parameters may include one or more of: a gain setting, an RF filter setting, an RF front end switch setting, a DC offset setting, or an IQ compensation setting for a radio subsystem, or a digital DC correction setting, a digital gain setting, and/or a digital filtering setting (e.g. for a baseband subsystem). The CI may also be associated with information associated with a time period, time signature, timestamp, time amplitude, time phase, time trend, and/or time characteristics of the signal. The CI may be associated with information associated with a time-frequency partition, signature, amplitude, phase, trend, and/or characteristics of the signal. The CI may be associated with a decomposition of the signal. The CI may be associated with information associated with a direction, angle of arrival (AoA), angle of

a directional antenna, and/or a phase of the signal through the channel. The CI may be associated with attenuation patterns of the signal through the channel. Each CI may be associated with a Type 1 device and a Type 2 device. Each CI may be associated with an antenna of the Type 1 device and an antenna of the Type 2 device.

The CI may be obtained from a communication hardware (e.g. of Type 2 device, or Type 1 device) that is capable of providing the CI. The communication hardware may be a WiFi-capable chip/IC (integrated circuit), chip compliant with a 802.11 or 802.16 or another wireless/radio standard, next generation WiFi-capable chip, LTE-capable chip, 5G-capable chip, 6G/7G/8G-capable chip, Bluetooth-enabled chip, NFC (near field communication)-enabled chip, BLE (Bluetooth low power)-enabled chip, UWB chip, another communication chip (e.g. Zigbee, WiMax, mesh network), etc. The communication hardware computes the CI and stores the CI in a buffer memory and make the CI available for extraction. The CI may comprise data and/or at least one matrices related to channel state information (CSI). The at least one matrices may be used for channel equalization, and/or beam forming, etc. The channel may be associated with a venue. The attenuation may be due to signal propagation in the venue, signal propagating/reflection/refraction/diffraction through/at/around air (e.g. air of venue), refraction medium/reflection surface such as wall, doors, furniture, obstacles and/or barriers, etc. The attenuation may be due to reflection at surfaces and obstacles (e.g. reflection surface, obstacle) such as floor, ceiling, furniture, fixtures, objects, people, pets, etc. Each CI may be associated with a timestamp. Each CI may comprise N1 components (e.g. N1 frequency domain components in CFR, N1 time domain components in CIR, or N1 decomposition components). Each component may be associated with a component index. Each component may be a real, imaginary, or complex quantity, magnitude, phase, flag, and/or set. Each CI may comprise a vector or matrix of complex numbers, a set of mixed quantities, and/or a multi-dimensional collection of at least one complex numbers.

Components of a TSCI associated with a particular component index may form a respective component time series associated with the respective index. A TSCI may be divided into N1 component time series. Each respective component time series is associated with a respective component index. The characteristics/STI of the motion of the object may be monitored based on the component time series. In one example, one or more ranges of CI components (e.g. one range being from component **11** to component **23**, a second range being from component **44** to component **50**, and a third range having only one component) may be selected based on some criteria/cost function/signal quality metric (e.g. based on signal-to-noise ratio, and/or interference level) for further processing.

A component-wise characteristic of a component-feature time series of a TSCI may be computed. The component-wise characteristics may be a scalar (e.g. energy) or a function with a domain and a range (e.g. an autocorrelation function, transform, inverse transform). The characteristics/STI of the motion of the object may be monitored based on the component-wise characteristics. A total characteristics (e.g. aggregate characteristics) of the TSCI may be computed based on the component-wise characteristics of each component time series of the TSCI. The total characteristics may be a weighted average of the component-wise characteristics. The characteristics/STI of the motion of the object



may be monitored based on the total characteristics. An aggregate quantity may be a weighted average of individual quantities.

The Type 1 device and Type 2 device may support WiFi, WiMax, 3G/beyond 3G, 4G/beyond 4G, LTE, LTE-A, 5G, 6G, 7G, Bluetooth, NFC, BLE, Zigbee, UWB, UMTS, 3GPP, GSM, EDGE, TDMA, FDMA, CDMA, WCDMA, TD-SCDMA, mesh network, proprietary wireless system, IEEE 802.11 standard, 802.15 standard, 802.16 standard, 3GPP standard, and/or another wireless system.

A common wireless system and/or a common wireless channel may be shared by the Type 1 transceiver and/or the at least one Type 2 transceiver. The at least one Type 2 transceiver may transmit respective signal contemporaneously (or: asynchronously, synchronously, sporadically, continuously, repeatedly, concurrently, simultaneously and/or temporarily) using the common wireless system and/or the common wireless channel. The Type 1 transceiver may transmit a signal to the at least one Type 2 transceiver using the common wireless system and/or the common wireless channel.

Each Type 1 device and Type 2 device may have at least one transmitting/receiving antenna. Each CI may be associated with one of the transmitting antenna of the Type 1 device and one of the receiving antenna of the Type 2 device. Each pair of a transmitting antenna and a receiving antenna may be associated with a link, a path, a communication path, signal hardware path, etc. For example, if the Type 1 device has M (e.g. 3) transmitting antennas, and the Type 2 device has N (e.g. 2) receiving antennas, there may be M×N (e.g. 3×2=6) links or paths. Each link or path may be associated with a TSCI.

The at least one TSCI may correspond to various antenna pairs between the Type 1 device and the Type 2 device. The Type 1 device may have at least one antenna. The Type 2 device may also have at least one antenna. Each TSCI may be associated with an antenna of the Type 1 device and an antenna of the Type 2 device. Averaging or weighted averaging over antenna links may be performed. The averaging or weighted averaging may be over the at least one TSCI. The averaging may optionally be performed on a subset of the at least one TSCI corresponding to a subset of the antenna pairs.

Timestamps of CI of a portion of a TSCI may be irregular and may be corrected so that corrected timestamps of time-corrected CI may be uniformly spaced in time. In the case of multiple Type 1 devices and/or multiple Type 2 devices, the corrected timestamp may be with respect to the same or different clock. An original timestamp associated with each of the CI may be determined. The original timestamp may not be uniformly spaced in time. Original timestamps of all CI of the particular portion of the particular TSCI in the current sliding time window may be corrected so that corrected timestamps of time-corrected CI may be uniformly spaced in time.

The characteristics and/or STI (e.g. motion information) may comprise: location, location coordinate, change in location, position (e.g. initial position, new position), position on map, height, horizontal location, vertical location, distance, displacement, speed, acceleration, rotational speed, rotational acceleration, direction, angle of motion, azimuth, direction of motion, rotation, path, deformation, transformation, shrinking, expanding, gait, gait cycle, head motion, repeated motion, periodic motion, pseudo-periodic motion, impulsive motion, sudden motion, fall-down motion, transient motion, behavior, transient behavior, period of motion, frequency of motion, time trend, temporal

profile, temporal characteristics, occurrence, change, temporal change, change of CI, change in frequency, change in timing, change of gait cycle, timing, starting time, initiating time, ending time, duration, history of motion, motion type, motion classification, frequency, frequency spectrum, frequency characteristics, presence, absence, proximity, approaching, receding, identity/identifier of the object, composition of the object, head motion rate, head motion direction, mouth-related rate, eye-related rate, breathing rate, heart rate, tidal volume, depth of breath, inhale time, exhale time, inhale time to exhale time ratio, airflow rate, heart heat-to-beat interval, heart rate variability, hand motion rate, hand motion direction, leg motion, body motion, walking rate, hand motion rate, positional characteristics, characteristics associated with movement (e.g. change in position/location) of the object, tool motion, machine motion, complex motion, and/or combination of multiple motions, event, signal statistics, signal dynamics, anomaly, motion statistics, motion parameter, indication of motion detection, motion magnitude, motion phase, similarity score, distance score, Euclidean distance, weighted distance, L<sub>1</sub> norm, L<sub>2</sub> norm, L<sub>k</sub> norm for k>2, statistical distance, correlation, correlation indicator, auto-correlation, covariance, auto-covariance, cross-covariance, inner product, outer product, motion signal transformation, motion feature, presence of motion, absence of motion, motion localization, motion identification, motion recognition, presence of object, absence of object, entrance of object, exit of object, a change of object, motion cycle, motion count, gait cycle, motion rhythm, deformation motion, gesture, handwriting, head motion, mouth motion, heart motion, internal organ motion, motion trend, size, length, area, volume, capacity, shape, form, tag, starting/initiating location, ending location, starting/initiating quantity, ending quantity, event, fall-down event, security event, accident event, home event, office event, factory event, warehouse event, manufacturing event, assembly line event, maintenance event, car-related event, navigation event, tracking event, door event, door-open event, door-close event, window event, window-open event, window-close event, repeatable event, one-time event, consumed quantity, unconsumed quantity, state, physical state, health state, well-being state, emotional state, mental state, another event, analytics, output responses, and/or another information. The characteristics and/or STI may be computed/monitored based on a feature computed from a CI or a TSCI (e.g. feature computation/extraction). A static segment or profile (and/or a dynamic segment/profile) may be identified/computed/analyzed/monitored/extracted/obtained/marked/presented/indicated/highlighted/stored/communicated based on an analysis of the feature. The analysis may comprise a motion detection/movement assessment/presence detection. Computational workload may be shared among the Type 1 device, the Type 2 device and another processor.

The Type 1 device and/or Type 2 device may be a local device. The local device may be: a smart phone, smart device, TV, sound bar, set-top box, access point, router, repeater, wireless signal repeater/extender, remote control, speaker, fan, refrigerator, microwave, oven, coffee machine, hot water pot, utensil, table, chair, light, lamp, door lock, camera, microphone, motion sensor, security device, fire hydrant, garage door, switch, power adapter, computer, dongle, computer peripheral, electronic pad, sofa, tile, accessory, home device, vehicle device, office device, building device, manufacturing device, watch, glasses, clock, television, oven, air-conditioner, accessory, utility, appliance, smart machine, smart vehicle, internet-of-thing (IoT)



device, internet-enabled device, computer, portable computer, tablet, smart house, smart office, smart building, smart parking lot, smart system, and/or another device.

Each Type 1 device may be associated with a respective identifier (e.g. ID). Each Type 2 device may also be associated with a respective identify (ID). The ID may comprise: numeral, combination of text and numbers, name, password, account, account ID, web link, web address, index to some information, and/or another ID. The ID may be assigned. The ID may be assigned by hardware (e.g. hardwired, via dongle and/or other hardware), software and/or firmware. The ID may be stored (e.g. in database, in memory, in server (e.g. hub device), in the cloud, stored locally, stored remotely, stored permanently, stored temporarily) and may be retrieved. The ID may be associated with at least one record, account, user, household, address, phone number, social security number, customer number, another ID, another identifier, timestamp, and/or collection of data. The ID and/or part of the ID of a Type 1 device may be made available to a Type 2 device. The ID may be used for registration, initialization, communication, identification, verification, detection, recognition, authentication, access control, cloud access, networking, social networking, logging, recording, cataloging, classification, tagging, association, pairing, transaction, electronic transaction, and/or intellectual property control, by the Type 1 device and/or the Type 2 device.

The object may be person, user, subject, passenger, child, older person, baby, sleeping baby, baby in vehicle, patient, worker, high-value worker, expert, specialist, waiter, customer in mall, traveler in airport/train station/bus terminal/shipping terminals, staff/worker/customer service personnel in factory/mall/supermarket/office/workplace, serviceman in sewage/air ventilation system/lift well, lifts in lift wells, elevator, inmate, people to be tracked/monitored, animal, plant, living object, pet, dog, cat, smart phone, phone accessory, computer, tablet, portable computer, dongle, computing accessory, networked devices, WiFi devices, IoT devices, smart watch, smart glasses, smart devices, speaker, keys, smart key, wallet, purse, handbag, backpack, goods, cargo, luggage, equipment, motor, machine, air conditioner, fan, air conditioning equipment, light fixture, moveable light, television, camera, audio and/or video equipment, stationary, surveillance equipment, parts, signage, tool, cart, ticket, parking ticket, toll ticket, airplane ticket, credit card, plastic card, access card, food packaging, utensil, table, chair, cleaning equipment/tool, vehicle, car, cars in parking facilities, merchandise in warehouse/store/supermarket/distribution center, boat, bicycle, airplane, drone, remote control car/plane/boat, robot, manufacturing device, assembly line, material/unfinished part/robot/wagon/transport on factory floor, object to be tracked in airport/shopping mart/supermarket, non-object, absence of an object, presence of an object, object with form, object with changing form, object with no form, mass of fluid, mass of liquid, mass of gas/smoke, fire, flame, electromagnetic (EM) source, EM medium, and/or another object.

The object itself may be communicatively coupled with some network, such as WiFi, MiFi, 3G/4G/LTE/5G/6G/7G, Bluetooth, NFC, BLE, WiMax, Zigbee, UMTS, 3GPP, GSM, EDGE, TDMA, FDMA, CDMA, WCDMA, TD-SCDMA, mesh network, adhoc network, and/or other network. The object itself may be bulky with AC power supply, but is moved during installation, cleaning, maintenance, renovation, etc. It may also be installed in moveable platform such as lift, pad, movable, platform, elevator, conveyor belt, robot, drone, forklift, car, boat, vehicle, etc. The object

may have multiple parts, each part with different movement (e.g. change in position/location). For example, the object may be a person walking forward. While walking, his left hand and right hand may move in different direction, with different instantaneous speed, acceleration, motion, etc.

The wireless transmitter (e.g. Type 1 device), the wireless receiver (e.g. Type 2 device), another wireless transmitter and/or another wireless receiver may move with the object and/or another object (e.g. in prior movement, current movement and/or future movement). They may be communicatively coupled to one or more nearby device. They may transmit TSCI and/or information associated with the TSCI to the nearby device, and/or each other. They may be with the nearby device. The wireless transmitter and/or the wireless receiver may be part of a small (e.g. coin-size, cigarette box size, or even smaller), light-weight portable device. The portable device may be wirelessly coupled with a nearby device.

The nearby device may be smart phone, iPhone, Android phone, smart device, smart appliance, smart vehicle, smart gadget, smart TV, smart refrigerator, smart speaker, smart watch, smart glasses, smart pad, iPad, computer, wearable computer, notebook computer, gateway. The nearby device may be connected to a cloud server, local server (e.g. hub device) and/or other server via internet, wired internet connection and/or wireless internet connection. The nearby device may be portable. The portable device, the nearby device, a local server (e.g. hub device) and/or a cloud server may share the computation and/or storage for a task (e.g. obtain TSCI, determine characteristics/STI of the object associated with the movement (e.g. change in position/location) of the object, computation of time series of power (e.g. signal strength) information, determining/computing the particular function, searching for local extremum, classification, identifying particular value of time offset, denoising, processing, simplification, cleaning, wireless smart sensing task, extract CI from signal, switching, segmentation, estimate trajectory/path/track, process the map, processing trajectory/path/track based on environment models/constraints/limitations, correction, corrective adjustment, adjustment, map-based (or model-based) correction, detecting error, checking for boundary hitting, thresholding) and information (e.g. TSCI). The nearby device may/may not move with the object. The nearby device may be portable/not portable/moveable/non-moveable. The nearby device may use battery power, solar power, AC power and/or other power source. The nearby device may have replaceable/non-replaceable battery, and/or rechargeable/non-rechargeable battery. The nearby device may be similar to the object. The nearby device may have identical (and/or similar) hardware and/or software to the object. The nearby device may be a smart device, network enabled device, device with connection to WiFi/3G/4G/5G/6G/Zigbee/Bluetooth/NFC/UMTS/3GPP/GSM/EDGE/TDMA/FDMA/CDMA/WCDMA/TD-SCDMA/adhoc network/other network, smart speaker, smart watch, smart clock, smart appliance, smart machine, smart equipment, smart tool, smart vehicle, internet-of-thing (IoT) device, internet-enabled device, computer, portable computer, tablet, and another device. The nearby device and/or at least one processor associated with the wireless receiver, the wireless transmitter, the another wireless receiver, the another wireless transmitter and/or a cloud server (in the cloud) may determine the initial STI of the object. Two or more of them may determine the initial spatial-temporal info jointly. Two or more of them may share intermediate information in the determination of the initial STI (e.g. initial position).



In one example, the wireless transmitter (e.g. Type 1 device, or Tracker Bot) may move with the object. The wireless transmitter may send the signal to the wireless receiver (e.g. Type 2 device, or Origin Register) or determining the initial STI (e.g. initial position) of the object. The wireless transmitter may also send the signal and/or another signal to another wireless receiver (e.g. another Type 2 device, or another Origin Register) for the monitoring of the motion (spatial-temporal info) of the object. The wireless receiver may also receive the signal and/or another signal from the wireless transmitter and/or the another wireless transmitter for monitoring the motion of the object. The location of the wireless receiver and/or the another wireless receiver may be known. In another example, the wireless receiver (e.g. Type 2 device, or Tracker Bot) may move with the object. The wireless receiver may receive the signal transmitted from the wireless transmitter (e.g. Type 1 device, or Origin Register) for determining the initial spatial-temporal info (e.g. initial position) of the object. The wireless receiver may also receive the signal and/or another signal from another wireless transmitter (e.g. another Type 1 device, or another Origin Register) for the monitoring of the current motion (e.g. spatial-temporal info) of the object. The wireless transmitter may also transmit the signal and/or another signal to the wireless receiver and/or the another wireless receiver (e.g. another Type 2 device, or another Tracker Bot) for monitoring the motion of the object. The location of the wireless transmitter and/or the another wireless transmitter may be known.

The venue may be a space such as a sensing area, room, house, office, property, workplace, hallway, walkway, lift, lift well, escalator, elevator, sewage system, air ventilations system, staircase, gathering area, duct, air duct, pipe, tube, enclosed space, enclosed structure, semi-enclosed structure, enclosed area, area with at least one wall, plant, machine, engine, structure with wood, structure with glass, structure with metal, structure with walls, structure with doors, structure with gaps, structure with reflection surface, structure with fluid, building, roof top, store, factory, assembly line, hotel room, museum, classroom, school, university, government building, warehouse, garage, mall, airport, train station, bus terminal, hub, transportation hub, shipping terminal, government facility, public facility, school, university, entertainment facility, recreational facility, hospital, pediatric/neonatal wards, seniors home, elderly care facility, geriatric facility, community center, stadium, playground, park, field, sports facility, swimming facility, track and/or field, basketball court, tennis court, soccer stadium, baseball stadium, gymnasium, hall, garage, shopping mart, mall, supermarket, manufacturing facility, parking facility, construction site, mining facility, transportation facility, highway, road, valley, forest, wood, terrain, landscape, den, patio, land, path, amusement park, urban area, rural area, suburban area, metropolitan area, garden, square, plaza, music hall, downtown facility, over-air facility, semi-open facility, closed area, train platform, train station, distribution center, warehouse, store, distribution center, storage facility, underground facility, space (e.g. above ground, outer-space) facility, floating facility, cavern, tunnel facility, indoor facility, open-air facility, outdoor facility with some walls/doors/reflective barriers, open facility, semi-open facility, car, truck, bus, van, container, ship/boat, submersible, train, tram, airplane, vehicle, mobile home, cave, tunnel, pipe, channel, metropolitan area, downtown area with relatively tall buildings, valley, well, duct, pathway, gas line, oil line, water pipe, network of interconnecting pathways/alleys/roads/tubes/cavities/caves/pipe-like structure/air space/fluid

space, human body, animal body, body cavity, organ, bone, teeth, soft tissue, hard tissue, rigid tissue, non-rigid tissue, blood/body fluid vessel, windpipe, air duct, den, etc. The venue may be indoor space, outdoor space, The venue may include both the inside and outside of the space. For example, the venue may include both the inside of a building and the outside of the building. For example, the venue can be a building that has one floor or multiple floors, and a portion of the building can be underground. The shape of the building can be, e.g., round, square, rectangular, triangle, or irregular-shaped. These are merely examples. The disclosure can be used to detect events in other types of venue or spaces.

The wireless transmitter (e.g. Type 1 device) and/or the wireless receiver (e.g. Type 2 device) may be embedded in a portable device (e.g. a module, or a device with the module) that may move with the object (e.g. in prior movement and/or current movement). The portable device may be communicatively coupled with the object using a wired connection (e.g. through USB, microUSB, Firewire, HDMI, serial port, parallel port, and other connectors) and/or a connection (e.g. Bluetooth, Bluetooth Low Energy (BLE), WiFi, LTE, NFC, ZigBee). The portable device may be a lightweight device. The portable may be powered by battery, rechargeable battery and/or AC power. The portable device may be very small (e.g. at sub-millimeter scale and/or sub-centimeter scale), and/or small (e.g. coin-size, card-size, pocket-size, or larger). The portable device may be large, sizable, and/or bulky (e.g. heavy machinery to be installed). The portable device may be a WiFi hotspot, access point, mobile WiFi (MiFi), dongle with USB/micro USB/Firewire/other connector, smartphone, portable computer, computer, tablet, smart device, internet-of-thing (IoT) device, WiFi-enabled device, LTE-enabled device, a smart watch, smart glass, smart mirror, smart antenna, smart battery, smart light, smart pen, smart ring, smart door, smart window, smart clock, small battery, smart wallet, smart belt, smart handbag, smart clothing/garment, smart ornament, smart packaging, smart paper/book/magazine/poster/printed matter/signage/display/lighted system/lighting system, smart key/tool, smart bracelet/chain/necklace/wearable/accessory, smart pad/cushion, smart tile/block/brick/building material/other material, smart garbage can/waste container, smart food carriage/storage, smart ball/racket, smart chair/sofa/bed, smart shoe/footwear/carpet/mat/shoe rack, smart glove/hand wear/ring/hand ware, smart hat/headwear/makeup/sticker/tattoo, smart mirror, smart toy, smart pill, smart utensil, smart bottle/food container, smart tool, smart device, IoT device, WiFi enabled device, network enabled device, 3G/4G/5G/6G enabled device, UMTS devices, 3GPP devices, GSM devices, EDGE devices, TDMA devices, FDMA devices, CDMA devices, WCDMA devices, TD-SCDMA devices, embeddable device, implantable device, air conditioner, refrigerator, heater, furnace, furniture, oven, cooking device, television/set-top box (STB)/DVD player/audio player/video player/remote control, hi-fi, audio device, speaker, lamp/light, wall, door, window, roof, roof tile/shingle/structure/attic structure/device/feature/installation/fixtures, lawn mower/garden tools/yard tools/mechanics tools/garage tools/, garbage can/container, 20-ft/40-ft container, storage container, factory/manufacturing/production device, repair tools, fluid container, machine, machinery to be installed, vehicle, cart, wagon, warehouse vehicle, car, bicycle, motorcycle, boat, vessel, airplane, basket/box/bag/bucket/container, smart plate/cup/bowl/pot/mat/utensils/kitchen tools/kitchen devices/kitchen accessories/cabinets/tables/chairs/tiles/lights/water pipes/taps/gas range/oven



dishwashing machine/etc. The portable device may have a battery that may be replaceable, irreplaceable, rechargeable, and/or non-rechargeable. The portable device may be wirelessly charged. The portable device may be a smart payment card. The portable device may be a payment card used in parking lots, highways, entertainment parks, or other venues/facilities that need payment. The portable device may have an identity (ID)/identifier as described above.

An event may be monitored based on the TSCI. The event may be an object related event, such as fall-down of the object (e.g. an person and/or a sick person), rotation, hesitation, pause, impact (e.g. a person hitting a sandbag, door, window, bed, chair, table, desk, cabinet, box, another person, animal, bird, fly, table, chair, ball, bowling ball, tennis ball, football, soccer ball, baseball, basketball, volley ball), two-body action (e.g. a person letting go a balloon, catching a fish, molding a clay, writing a paper, person typing on a computer), car moving in a garage, person carrying a smart phone and walking around an airport/mall/government building/office/etc., autonomous moveable object/machine moving around (e.g. vacuum cleaner, utility vehicle, car, drone, self-driving car).

The task or the wireless smart sensing task may comprise: object detection, presence detection, proximity detection, object recognition, activity recognition, object verification, object counting, daily activity monitoring, well-being monitoring, vital sign monitoring, health condition monitoring, baby monitoring, elderly monitoring, sleep monitoring, sleep stage monitoring, walking monitoring, exercise monitoring, tool detection, tool recognition, tool verification, patient detection, patient monitoring, patient verification, machine detection, machine recognition, machine verification, human detection, human recognition, human verification, baby detection, baby recognition, baby verification, human breathing detection, human breathing recognition, human breathing estimation, human breathing verification, human heart beat detection, human heart beat recognition, human heart beat estimation, human heart beat verification, fall-down detection, fall-down recognition, fall-down estimation, fall-down verification, emotion detection, emotion recognition, emotion estimation, emotion verification, motion detection, motion degree estimation, motion recognition, motion estimation, motion verification, periodic motion detection, periodic motion recognition, periodic motion estimation, periodic motion verification, repeated motion detection, repeated motion recognition, repeated motion estimation, repeated motion verification, stationary motion detection, stationary motion recognition, stationary motion estimation, stationary motion verification, cyclo-stationary motion detection, cyclo-stationary motion recognition, cyclo-stationary motion estimation, cyclo-stationary motion verification, transient motion detection, transient motion recognition, transient motion estimation, transient motion verification, trend detection, trend recognition, trend estimation, trend verification, breathing detection, breathing recognition, breathing estimation, breathing verification, human biometrics detection, human biometric recognition, human biometrics estimation, human biometrics verification, environment informatics detection, environment informatics recognition, environment informatics estimation, environment informatics verification, gait detection, gait recognition, gait estimation, gait verification, gesture detection, gesture recognition, gesture estimation, gesture verification, machine learning, supervised learning, unsupervised learning, semi-supervised learning, clustering, feature extraction, featuring training, principal component analysis, eigen-decomposition, frequency decomposition, time

decomposition, time-frequency decomposition, functional decomposition, other decomposition, training, discriminative training, supervised training, unsupervised training, semi-supervised training, neural network, sudden motion detection, fall-down detection, danger detection, life-threat detection, regular motion detection, stationary motion detection, cyclo-stationary motion detection, intrusion detection, suspicious motion detection, security, safety monitoring, navigation, guidance, map-based processing, map-based correction, model-based processing/correction, irregularity detection, locationing, room sensing, tracking, multiple object tracking, indoor tracking, indoor position, indoor navigation, energy management, power transfer, wireless power transfer, object counting, car tracking in parking garage, activating a device/system (e.g. security system, access system, alarm, siren, speaker, television, entertaining system, camera, heater/air-conditioning (HVAC) system, ventilation system, lighting system, gaming system, coffee machine, cooking device, cleaning device, housekeeping device), geometry estimation, augmented reality, wireless communication, data communication, signal broadcasting, networking, coordination, administration, encryption, protection, cloud computing, other processing and/or other task. The task may be performed by the Type 1 device, the Type 2 device, another Type 1 device, another Type 2 device, a nearby device, a local server (e.g. hub device), edge server, a cloud server, and/or another device. The task may be based on TSCI between any pair of Type 1 device and Type 2 device. A Type 2 device may be a Type 1 device, and vice versa. A Type 2 device may play/perform the role (e.g. functionality) of Type 1 device temporarily, continuously, sporadically, simultaneously, and/or contemporaneously, and vice versa. A first part of the task may comprise at least one of: preprocessing, processing, signal conditioning, signal processing, post-processing, processing sporadically/continuously/simultaneously/contemporaneously/dynamically/adaptively/on-demand/as-needed, calibrating, denoising, feature extraction, coding, encryption, transformation, mapping, motion detection, motion estimation, motion change detection, motion pattern detection, motion pattern estimation, motion pattern recognition, vital sign detection, vital sign estimation, vital sign recognition, periodic motion detection, periodic motion estimation, repeated motion detection/estimation, breathing rate detection, breathing rate estimation, breathing pattern detection, breathing pattern estimation, breathing pattern recognition, heart beat detection, heart beat estimation, heart pattern detection, heart pattern estimation, heart pattern recognition, gesture detection, gesture estimation, gesture recognition, speed detection, speed estimation, object locationing, object tracking, navigation, acceleration estimation, acceleration detection, fall-down detection, change detection, intruder (and/or illegal action) detection, baby detection, baby monitoring, patient monitoring, object recognition, wireless power transfer, and/or wireless charging.

A second part of the task may comprise at least one of: a smart home task, smart office task, smart building task, smart factory task (e.g. manufacturing using a machine or an assembly line), smart internet-of-thing (IoT) task, smart system task, smart home operation, smart office operation, smart building operation, smart manufacturing operation (e.g. moving supplies/parts/raw material to a machine/an assembly line), IoT operation, smart system operation, turning on a light, turning off the light, controlling the light in at least one of: a room, region, and/or the venue, playing a sound clip, playing the sound clip in at least one of: the room, the region, and/or the venue, playing the sound clip of



at least one of: a welcome, greeting, farewell, first message, and/or a second message associated with the first part of the task, turning on an appliance, turning off the appliance, controlling the appliance in at least one of: the room, the region, and/or the venue, turning on an electrical system, turning off the electrical system, controlling the electrical system in at least one of: the room, the region, and/or the venue, turning on a security system, turning off the security system, controlling the security system in at least one of: the room, the region, and/or the venue, turning on a mechanical system, turning off a mechanical system, controlling the mechanical system in at least one of: the room, the region, and/or the venue, and/or controlling at least one of: an air conditioning system, heating system, ventilation system, lighting system, heating device, stove, entertainment system, door, fence, window, garage, computer system, networked device, networked system, home appliance, office equipment, lighting device, robot (e.g. robotic arm), smart vehicle, smart machine, assembly line, smart device, internet-of-thing (IoT) device, smart home device, and/or a smart office device.

The task may include: detect a user returning home, detect a user leaving home, detect a user moving from one room to another, detect/control/lock/unlock/open/close/partially open a window/door/garage door/blind/curtain/panel/solar panel/sun shade, detect a pet, detect/monitor a user doing something (e.g. sleeping on sofa, sleeping in bedroom, running on treadmill, cooking, sitting on sofa, watching TV, eating in kitchen, eating in dining room, going upstairs/downstairs, going outside/coming back, in the rest room), monitor/detect location of a user/pet, do something (e.g. send a message, notify/report to someone) automatically upon detection, do something for the user automatically upon detecting the user, turn on/off/dim a light, turn on/off music/radio/home entertainment system, turn on/off/adjust/control TV/HiFi/set-top-box (STB)/home entertainment system/smart speaker/smart device, turn on/off/adjust air conditioning system, turn on/off/adjust ventilation system, turn on/off/adjust heating system, adjust/control curtains/light shades, turn on/off/wake a computer, turn on/off/pre-heat/control coffee machine/hot water pot, turn on/off/control/preheat cooker/oven/microwave oven/another cooking device, check/adjust temperature, check weather forecast, check telephone message box, check mail, do a system check, control/adjust a system, check/control/arm/disarm security system/baby monitor, check/control refrigerator, give a report (e.g. through a speaker such as Google home, Amazon Echo, on a display/screen, via a webpage/email/messaging system/notification system).

For example, when a user arrives home in his car, the task may be to, automatically, detect the user or his car approaching, open the garage door upon detection, turn on the driveway/garage light as the user approaches the garage, turn on air conditioner/heater/fan, etc. As the user enters the house, the task may be to, automatically, turn on the entrance light, turn off driveway/garage light, play a greeting message to welcome the user, turn on the music, turn on the radio and tuning to the user's favorite radio news channel, open the curtain/blind, monitor the user's mood, adjust the lighting and sound environment according to the user's mood or the current/imminent event (e.g. do romantic lighting and music because the user is scheduled to eat dinner with girlfriend in 1 hour) on the user's daily calendar, warm the food in microwave that the user prepared in the morning, do a diagnostic check of all systems in the house, check weather forecast for tomorrow's work, check news of interest to the user, check user's calendar and to-do list and play reminder,

check telephone answer system/messaging system/email and give a verbal report using dialog system/speech synthesis, remind (e.g. using audible tool such as speakers/HiFi/speech synthesis/sound/voice/music/song/sound field/background sound field/dialog system, using visual tool such as TV/entertainment system/computer/notebook/smart pad/display/light/color/brightness/patterns/symbols, using haptic tool/virtual reality tool/gesture/tool, using a smart device/appliance/material/furniture/fixture, using web tool/server/hub device/cloud server/fog server/edge server/home network/mesh network, using messaging tool/notification tool/communication tool/scheduling tool/email, using user interface/GUI, using scent/smell/fragrance/taste, using neural tool/nervous system tool, using a combination) the user of his mother's birthday and to call her, prepare a report, and give the report (e.g. using a tool for reminding as discussed above). The task may turn on the air conditioner/heater/ventilation system in advance, or adjust temperature setting of smart thermostat in advance, etc. As the user moves from the entrance to the living room, the task may be to turn on the living room light, open the living room curtain, open the window, turn off the entrance light behind the user, turn on the TV and set-top box, set TV to the user's favorite channel, adjust an appliance according to the user's preference and conditions/states (e.g. adjust lighting and choose/play music to build a romantic atmosphere), etc.

Another example may be: When the user wakes up in the morning, the task may be to detect the user moving around in the bedroom, open the blind/curtain, open the window, turn off the alarm clock, adjust indoor temperature from night-time temperature profile to day-time temperature profile, turn on the bedroom light, turn on the restroom light as the user approaches the restroom, check radio or streaming channel and play morning news, turn on the coffee machine and preheat the water, turn off security system, etc. When the user walks from bedroom to kitchen, the task may be to turn on the kitchen and hallway lights, turn off the bedroom and restroom lights, move the music/message/reminder from the bedroom to the kitchen, turn on the kitchen TV, change TV to morning news channel, lower the kitchen blind and open the kitchen window to bring in fresh air, unlock backdoor for the user to check the backyard, adjust temperature setting for the kitchen, etc. Another example may be: When the user leaves home for work, the task may be to detect the user leaving, play a farewell and/or have-a-good-day message, open/close garage door, turn on/off garage light and driveway light, turn off/dim lights to save energy (just in case the user forgets), close/lock all windows/doors (just in case the user forgets), turn off appliance (especially stove, oven, microwave oven), turn on/arm the home security system to guard the home against any intruder, adjust air conditioning/heating/ventilation systems to "away-from-home" profile to save energy, send alerts/reports/updates to the user's smart phone, etc.

A motion may comprise at least one of: a no-motion, resting motion, non-moving motion, movement, change in position/location, deterministic motion, transient motion, fall-down motion, repeating motion, periodic motion, pseudo-periodic motion, periodic/repeated motion associated with breathing, periodic/repeated motion associated with heartbeat, periodic/repeated motion associated with living object, periodic/repeated motion associated with machine, periodic/repeated motion associated with man-made object, periodic/repeated motion associated with nature, complex motion with transient element and periodic element, repetitive motion, non-deterministic motion, probabilistic motion, chaotic motion, random motion, com-



plex motion with non-deterministic element and deterministic element, stationary random motion, pseudo-stationary random motion, cyclo-stationary random motion, non-stationary random motion, stationary random motion with periodic autocorrelation function (ACF), random motion with periodic ACF for period of time, random motion that is pseudo-stationary for a period of time, random motion of which an instantaneous ACF has a pseudo-periodic/repeating element for a period of time, machine motion, mechanical motion, vehicle motion, drone motion, air-related motion, wind-related motion, weather-related motion, water-related motion, fluid-related motion, ground-related motion, change in electro-magnetic characteristics, sub-surface motion, seismic motion, plant motion, animal motion, human motion, normal motion, abnormal motion, dangerous motion, warning motion, suspicious motion, rain, fire, flood, tsunami, explosion, collision, imminent collision, human body motion, head motion, facial motion, eye motion, mouth motion, tongue motion, neck motion, finger motion, hand motion, arm motion, shoulder motion, body motion, chest motion, abdominal motion, hip motion, leg motion, foot motion, body joint motion, knee motion, elbow motion, upper body motion, lower body motion, skin motion, below-skin motion, subcutaneous tissue motion, blood vessel motion, intravenous motion, organ motion, heart motion, lung motion, stomach motion, intestine motion, bowel motion, eating motion, breathing motion, facial expression, eye expression, mouth expression, talking motion, singing motion, eating motion, gesture, hand gesture, arm gesture, keystroke, typing stroke, user-interface gesture, man-machine interaction, gait, dancing movement, coordinated movement, and/or coordinated body movement.

The heterogeneous IC of the Type 1 device and/or any Type 2 receiver may comprise low-noise amplifier (LNA), power amplifier, transmit-receive switch, media access controller, baseband radio, 2.4 GHz radio, 3.65 GHz radio, 4.9 GHz radio, 5 GHz radio, 5.9 GHz radio, below 6 GHz radio, below 60 GHz radio and/or another radio. The heterogeneous IC may comprise a processor, a memory communicatively coupled with the processor, and a set of instructions stored in the memory to be executed by the processor. The IC and/or any processor may comprise at least one of: general purpose processor, special purpose processor, microprocessor, multi-processor, multi-core processor, parallel processor, CISC processor, RISC processor, microcontroller, central processing unit (CPU), graphical processor unit (GPU), digital signal processor (DSP), application specific integrated circuit (ASIC), field programmable gate array (FPGA), embedded processor (e.g. ARM), logic circuit, other programmable logic device, discrete logic, and/or a combination. The heterogeneous IC may support broadband network, wireless network, mobile network, mesh network, cellular network, wireless local area network (WLAN), wide area network (WAN), and metropolitan area network (MAN), WLAN standard, WiFi, LTE, LTE-A, LTE-U, 802.11 standard, 802.11a, 802.11b, 802.11g, 802.11n, 802.11ac, 802.11ad, 802.11af, 802.11ah, 802.11ax, 802.11ay, mesh network standard, 802.15 standard, 802.16 standard, cellular network standard, 3G, 3.5G, 4G, beyond 4G, 4.5G, 5G, 6G, 7G, 8G, 9G, UMTS, 3GPP, GSM, EDGE, TDMA, FDMA, CDMA, WCDMA, TD-SCDMA, Bluetooth, Bluetooth Low-Energy (BLE), NFC, Zigbee, WiMax, and/or another wireless network protocol.

The processor may comprise general purpose processor, special purpose processor, microprocessor, microcontroller, embedded processor, digital signal processor, central processing unit (CPU), graphical processing unit (GPU), multi-

processor, multi-core processor, and/or processor with graphics capability, and/or a combination. The memory may be volatile, non-volatile, random access memory (RAM), Read Only Memory (ROM), Electrically Programmable ROM (EPROM), Electrically Erasable Programmable ROM (EEPROM), hard disk, flash memory, CD-ROM, DVD-ROM, magnetic storage, optical storage, organic storage, storage system, storage network, network storage, cloud storage, edge storage, local storage, external storage, internal storage, or other form of non-transitory storage medium known in the art. The set of instructions (machine executable code) corresponding to the method steps may be embodied directly in hardware, in software, in firmware, or in combinations thereof. The set of instructions may be embedded, pre-loaded, loaded upon boot up, loaded on the fly, loaded on demand, pre-installed, installed, and/or downloaded.

The presentation may be a presentation in an audio-visual way (e.g. using combination of visual, graphics, text, symbols, color, shades, video, animation, sound, speech, audio, etc.), graphical way (e.g. using GUI, animation, video), textual way (e.g. webpage with text, message, animated text), symbolic way (e.g. emoticon, signs, hand gesture), or mechanical way (e.g. vibration, actuator movement, haptics, etc.).

#### Basic Computation

Computational workload associated with the method is shared among the processor, the Type 1 heterogeneous wireless device, the Type 2 heterogeneous wireless device, a local server (e.g. hub device), a cloud server, and another processor.

An operation, pre-processing, processing and/or postprocessing may be applied to data (e.g. TSCI, autocorrelation, features of TSCI). An operation may be preprocessing, processing and/or postprocessing. The preprocessing, processing and/or postprocessing may be an operation. An operation may comprise preprocessing, processing, postprocessing, scaling, computing a confidence factor, computing a line-of-sight (LOS) quantity, computing a non-LOS (NLOS) quantity, a quantity comprising LOS and NLOS, computing a single link (e.g. path, communication path, link between a transmitting antenna and a receiving antenna) quantity, computing a quantity comprising multiple links, computing a function of the operands, filtering, linear filtering, nonlinear filtering, folding, grouping, energy computation, lowpass filtering, bandpass filtering, highpass filtering, median filtering, rank filtering, quartile filtering, percentile filtering, mode filtering, finite impulse response (FIR) filtering, infinite impulse response (IIR) filtering, moving average (MA) filtering, autoregressive (AR) filtering, autoregressive moving averaging (ARMA) filtering, selective filtering, adaptive filtering, interpolation, decimation, subsampling, upsampling, resampling, time correction, time base correction, phase correction, magnitude correction, phase cleaning, magnitude cleaning, matched filtering, enhancement, restoration, denoising, smoothing, signal conditioning, enhancement, restoration, spectral analysis, linear transform, nonlinear transform, inverse transform, frequency transform, inverse frequency transform, Fourier transform (FT), discrete time FT (DTFT), discrete FT (DFT), fast FT (FFT), wavelet transform, Laplace transform, Hilbert transform, Hadamard transform, trigonometric transform, sine transform, cosine transform, DCT, power-of-2 transform, sparse transform, graph-based transform, graph signal processing, fast transform, a transform combined with zero padding, cyclic padding, padding, zero padding, feature extraction, decomposition, projection, orthogonal projection, non-orthogonal projection, over-complete projection,



eigen-decomposition, singular value decomposition (SVD), principle component analysis (PCA), independent component analysis (ICA), grouping, sorting, thresholding, soft thresholding, hard thresholding, clipping, soft clipping, first derivative, second order derivative, high order derivative, convolution, multiplication, division, addition, subtraction, integration, maximization, minimization, least mean square error, recursive least square, constrained least square, batch least square, least absolute error, least mean square deviation, least absolute deviation, local maximization, local minimization, optimization of a cost function, neural network, recognition, labeling, training, clustering, machine learning, supervised learning, unsupervised learning, semi-supervised learning, comparison with another TSCI, similarity score computation, quantization, vector quantization, matching pursuit, compression, encryption, coding, storing, transmitting, normalization, temporal normalization, frequency domain normalization, classification, clustering, labeling, tagging, learning, detection, estimation, learning network, mapping, remapping, expansion, storing, retrieving, transmitting, receiving, representing, merging, combining, splitting, tracking, monitoring, matched filtering, Kalman filtering, particle filter, interpolation, extrapolation, histogram estimation, importance sampling, Monte Carlo sampling, compressive sensing, representing, merging, combining, splitting, scrambling, error protection, forward error correction, doing nothing, time varying processing, conditioning averaging, weighted averaging, arithmetic mean, geometric mean, harmonic mean, averaging over selected frequency, averaging over antenna links, logical operation, permutation, combination, sorting, AND, OR, XOR, union, intersection, vector addition, vector subtraction, vector multiplication, vector division, inverse, norm, distance, and/or another operation. The operation may be the preprocessing, processing, and/or post-processing. Operations may be applied jointly on multiple time series or functions.

The function (e.g. function of operands) may comprise: scalar function, vector function, discrete function, continuous function, polynomial function, characteristics, feature, magnitude, phase, exponential function, logarithmic function, trigonometric function, transcendental function, logical function, linear function, algebraic function, nonlinear function, piecewise linear function, real function, complex function, vector-valued function, inverse function, derivative of function, integration of function, circular function, function of another function, one-to-one function, one-to-many function, many-to-one function, many-to-many function, zero crossing, absolute function, indicator function, mean, mode, median, range, statistics, histogram, variance, standard deviation, measure of variation, spread, dispersion, deviation, divergence, range, interquartile range, total variation, absolute deviation, total deviation, arithmetic mean, geometric mean, harmonic mean, trimmed mean, percentile, square, cube, root, power, sine, cosine, tangent, cotangent, secant, cosecant, elliptical function, parabolic function, hyperbolic function, game function, zeta function, absolute value, thresholding, limiting function, floor function, rounding function, sign function, quantization, piecewise constant function, composite function, function of function, time function processed with an operation (e.g. filtering), probabilistic function, stochastic function, random function, ergodic function, stationary function, deterministic function, periodic function, repeated function, transformation, frequency transform, inverse frequency transform, discrete time transform, Laplace transform, Hilbert transform, sine transform, cosine transform, triangular transform, wavelet transform, integer transform, power-of-2 transform, sparse

transform, projection, decomposition, principle component analysis (PCA), independent component analysis (ICA), neural network, feature extraction, moving function, function of moving window of neighboring items of time series, filtering function, convolution, mean function, histogram, variance/standard deviation function, statistical function, short-time transform, discrete transform, discrete Fourier transform, discrete cosine transform, discrete sine transform, Hadamard transform, eigen-decomposition, eigenvalue, singular value decomposition (SVD), singular value, orthogonal decomposition, matching pursuit, sparse transform, sparse approximation, any decomposition, graph-based processing, graph-based transform, graph signal processing, classification, identifying a class/group/category, labeling, learning, machine learning, detection, estimation, feature extraction, learning network, feature extraction, denoising, signal enhancement, coding, encryption, mapping, remapping, vector quantization, lowpass filtering, highpass filtering, bandpass filtering, matched filtering, Kalman filtering, preprocessing, postprocessing, particle filter, FIR filtering, IIR filtering, autoregressive (AR) filtering, adaptive filtering, first order derivative, high order derivative, integration, zero crossing, smoothing, median filtering, mode filtering, sampling, random sampling, resampling function, downsampling, down-converting, upsampling, up-converting, interpolation, extrapolation, importance sampling, Monte Carlo sampling, compressive sensing, statistics, short term statistics, long term statistics, autocorrelation function, cross correlation, moment generating function, time averaging, weighted averaging, special function, Bessel function, error function, complementary error function, Beta function, Gamma function, integral function, Gaussian function, Poisson function, etc.

Machine learning, training, discriminative training, deep learning, neural network, continuous time processing, distributed computing, distributed storage, acceleration using GPU/DSP/coprocessor/multicore/multiprocessing may be applied to a step (or each step) of this disclosure.

A frequency transform may include Fourier transform, Laplace transform, Hadamard transform, Hilbert transform, sine transform, cosine transform, triangular transform, wavelet transform, integer transform, power-of-2 transform, combined zero padding and transform, Fourier transform with zero padding, and/or another transform. Fast versions and/or approximated versions of the transform may be performed. The transform may be performed using floating point, and/or fixed point arithmetic.

An inverse frequency transform may include inverse Fourier transform, inverse Laplace transform, inverse Hadamard transform, inverse Hilbert transform, inverse sine transform, inverse cosine transform, inverse triangular transform, inverse wavelet transform, inverse integer transform, inverse power-of-2 transform, combined zero padding and transform, inverse Fourier transform with zero padding, and/or another transform. Fast versions and/or approximated versions of the transform may be performed. The transform may be performed using floating point, and/or fixed point arithmetic.

A quantity/feature from a TSCI may be computed. The quantity may comprise statistic of at least one of: motion, location, map coordinate, height, speed, acceleration, movement angle, rotation, size, volume, time trend, pattern, one-time pattern, repeating pattern, evolving pattern, time pattern, mutually excluding patterns, related/correlated patterns, cause-and-effect, correlation, short-term/long-term correlation, tendency, inclination, statistics, typical behavior, atypical behavior, time trend, time profile, periodic



motion, repeated motion, repetition, tendency, change, abrupt change, gradual change, frequency, transient, breathing, gait, action, event, suspicious event, dangerous event, alarming event, warning, belief, proximity, collision, power, signal, signal power, signal strength, signal intensity, received signal strength indicator (RSSI), signal amplitude, signal phase, signal frequency component, signal frequency band component, channel state information (CSI), map, time, frequency, time-frequency, decomposition, orthogonal decomposition, non-orthogonal decomposition, tracking, breathing, heart beat, statistical parameters, cardiopulmonary statistics/analytics (e.g. output responses), daily activity statistics/analytics, chronic disease statistics/analytics, medical statistics/analytics, an early (or instantaneous or contemporaneous or delayed) indication/suggestion/sign/indicator/verifier/detection/symptom of a disease/condition/situation, biometric, baby, patient, machine, device, temperature, vehicle, parking lot, venue, lift, elevator, spatial, road, fluid flow, home, room, office, house, building, warehouse, storage, system, ventilation, fan, pipe, duct, people, human, car, boat, truck, airplane, drone, downtown, crowd, impulsive event, cyclo-stationary, environment, vibration, material, surface, 3-dimensional, 2-dimensional, local, global, presence, and/or another measurable quantity/variable.

#### Sliding Window/Algorithm

Sliding time window may have time varying window width. It may be smaller at the beginning to enable fast acquisition and may increase over time to a steady-state size. The steady-state size may be related to the frequency, repeated motion, transient motion, and/or STI to be monitored. Even in steady state, the window size may be adaptively (and/or dynamically) changed (e.g. adjusted, varied, modified) based on battery life, power consumption, available computing power, change in amount of targets, the nature of motion to be monitored, etc.

The time shift between two sliding time windows at adjacent time instance may be constant/variable/locally adaptive/dynamically adjusted over time. When shorter time shift is used, the update of any monitoring may be more frequent which may be used for fast changing situations, object motions, and/or objects. Longer time shift may be used for slower situations, object motions, and/or objects.

The window width/size and/or time shift may be changed (e.g. adjusted, varied, modified) upon a user request/choice. The time shift may be changed automatically (e.g. as controlled by processor/computer/server/hub device/cloud server) and/or adaptively (and/or dynamically).

At least one characteristics (e.g. characteristic value, or characteristic point) of a function (e.g. auto-correlation function, auto-covariance function, cross-correlation function, cross-covariance function, power spectral density, time function, frequency domain function, frequency transform) may be determined (e.g. by an object tracking server, the processor, the Type 1 heterogeneous device, the Type 2 heterogeneous device, and/or another device). The at least one characteristics of the function may include: a maximum, minimum, extremum, local maximum, local minimum, local extremum, local extremum with positive time offset, first local extremum with positive time offset,  $n^{\text{th}}$  local extremum with positive time offset, local extremum with negative time offset, first local extremum with negative time offset,  $n^{\text{th}}$  local extremum with negative time offset, constrained maximum, constrained minimum, constrained extremum, significant maximum, significant minimum, significant extremum, slope, derivative, higher order derivative, maximum slope, minimum slope, local maximum slope, local

maximum slope with positive time offset, local minimum slope, constrained maximum slope, constrained minimum slope, maximum higher order derivative, minimum higher order derivative, constrained higher order derivative, zero-crossing, zero crossing with positive time offset,  $n^{\text{th}}$  zero crossing with positive time offset, zero crossing with negative time offset,  $n^{\text{th}}$  zero crossing with negative time offset, constrained zero-crossing, zero-crossing of slope, zero-crossing of higher order derivative, and/or another characteristics. At least one argument of the function associated with the at least one characteristics of the function may be identified. Some quantity (e.g. spatial-temporal information of the object) may be determined based on the at least one argument of the function.

A characteristics (e.g. characteristics of motion of an object in the venue) may comprise at least one of: an instantaneous characteristics, short-term characteristics, repetitive characteristics, recurring characteristics, history, incremental characteristics, changing characteristics, deviational characteristics, phase, magnitude, degree, time characteristics, frequency characteristics, time-frequency characteristics, decomposition characteristics, orthogonal decomposition characteristics, non-orthogonal decomposition characteristics, deterministic characteristics, probabilistic characteristics, stochastic characteristics, autocorrelation function (ACF), mean, variance, standard deviation, measure of variation, spread, dispersion, deviation, divergence, range, interquartile range, total variation, absolute deviation, total deviation, statistics, duration, timing, trend, periodic characteristics, repetition characteristics, long-term characteristics, historical characteristics, average characteristics, current characteristics, past characteristics, future characteristics, predicted characteristics, location, distance, height, speed, direction, velocity, acceleration, change of the acceleration, angle, angular speed, angular velocity, angular acceleration of the object, change of the angular acceleration, orientation of the object, angular of rotation, deformation of the object, shape of the object, change of shape of the object, change of size of the object, change of structure of the object, and/or change of characteristics of the object.

At least one local maximum and at least one local minimum of the function may be identified. At least one local signal-to-noise-ratio-like (SNR-like) parameter may be computed for each pair of adjacent local maximum and local minimum. The SNR-like parameter may be a function (e.g. linear, log, exponential function, monotonic function) of a fraction of a quantity (e.g. power, magnitude) of the local maximum over the same quantity of the local minimum. It may also be the function of a difference between the quantity of the local maximum and the same quantity of the local minimum. Significant local peaks may be identified or selected. Each significant local peak may be a local maximum with SNR-like parameter greater than a threshold T1 and/or a local maximum with amplitude greater than a threshold T2. The at least one local minimum and the at least one local minimum in the frequency domain may be identified/computed using a persistence-based approach.

A set of selected significant local peaks may be selected from the set of identified significant local peaks based on a selection criterion (e.g. a quality criterion, a signal quality condition). The characteristics/STI of the object may be computed based on the set of selected significant local peaks and frequency values associated with the set of selected significant local peaks. In one example, the selection criterion may always correspond to select the strongest peaks in a range. While the strongest peaks may be selected, the unselected peaks may still be significant (rather strong).



Unselected significant peaks may be stored and/or monitored as “reserved” peaks for use in future selection in future sliding time windows. As an example, there may be a particular peak (at a particular frequency) appearing consistently over time. Initially, it may be significant but not selected (as other peaks may be stronger). But in later time, the peak may become stronger and more dominant and may be selected. When it became “selected”, it may be back-traced in time and made “selected” in the earlier time when it was significant but not selected. In such case, the back-traced peak may replace a previously selected peak in an early time. The replaced peak may be the relatively weakest, or a peak that appear in isolation in time (i.e. appearing only briefly in time).

In another example, the selection criterion may not correspond to select the strongest peaks in the range. Instead, it may consider not only the “strength” of the peak, but the “trace” of the peak—peaks that may have happened in the past, especially those peaks that have been identified for a long time.

For example, if a finite state machine (FSM) is used, it may select the peak(s) based on the state of the FSM. Decision thresholds may be computed adaptively (and/or dynamically) based on the state of the FSM.

A similarity score and/or component similarity score may be computed (e.g. by a server (e.g. hub device), the processor, the Type 1 device, the Type 2 device, a local server, a cloud server, and/or another device) based on a pair of temporally adjacent CI of a TSCI. The pair may come from the same sliding window or two different sliding windows. The similarity score may also be based on a pair of, temporally adjacent or not so adjacent, CI from two different TSCI. The similarity score and/or component similar score may be/comprise: time reversal resonating strength (TRRS), correlation, cross-correlation, auto-correlation, correlation indicator, covariance, cross-covariance, auto-covariance, inner product of two vectors, distance score, norm, metric, quality metric, signal quality condition, statistical characteristics, discrimination score, neural network, deep learning network, machine learning, training, discrimination, weighted averaging, preprocessing, denoising, signal conditioning, filtering, time correction, timing compensation, phase offset compensation, transformation, component-wise operation, feature extraction, finite state machine, and/or another score. The characteristics and/or STI may be determined/computed based on the similarity score.

Any threshold may be pre-determined, adaptively (and/or dynamically) determined and/or determined by a finite state machine. The adaptive determination may be based on time, space, location, antenna, path, link, state, battery life, remaining battery life, available power, available computational resources, available network bandwidth, etc.

A threshold to be applied to a test statistics to differentiate two events (or two conditions, or two situations, or two states), A and B, may be determined. Data (e.g. CI, channel state information (CSI), power parameter) may be collected under A and/or under B in a training situation. The test statistics may be computed based on the data. Distributions of the test statistics under A may be compared with distributions of the test statistics under B (reference distribution), and the threshold may be chosen according to some criteria. The criteria may comprise: maximum likelihood (ML), maximum a posterior probability (MAP), discriminative training, minimum Type 1 error for a given Type 2 error, minimum Type 2 error for a given Type 1 error, and/or other criteria (e.g. a quality criterion, signal quality condition). The threshold may be adjusted to achieve different sensi-

tivity to the A, B and/or another event/condition/situation/state. The threshold adjustment may be automatic, semi-automatic and/or manual. The threshold adjustment may be applied once, sometimes, often, periodically, repeatedly, occasionally, sporadically, and/or on demand. The threshold adjustment may be adaptive (and/or dynamically adjusted). The threshold adjustment may depend on the object, object movement/location/direction/action, object characteristics/STI/size/property/trait/habit/behavior, the venue, feature/fixture/furniture/barrier/material/machine/living thing/thing/object/boundary/surface/medium that is in/at/of the venue, map, constraint of the map (or environmental model), the event/state/situation/condition, time, timing, duration, current state, past history, user, and/or a personal preference, etc.

A stopping criterion (or skipping or bypassing or blocking or pausing or passing or rejecting criterion) of an iterative algorithm may be that change of a current parameter (e.g. offset value) in the updating in an iteration is less than a threshold. The threshold may be 0.5, 1, 1.5, 2, or another number. The threshold may be adaptive (and/or dynamically adjusted). It may change as the iteration progresses. For the offset value, the adaptive threshold may be determined based on the task, particular value of the first time, the current time offset value, the regression window, the regression analysis, the regression function, the regression error, the convexity of the regression function, and/or an iteration number.

The local extremum may be determined as the corresponding extremum of the regression function in the regression window. The local extremum may be determined based on a set of time offset values in the regression window and a set of associated regression function values. Each of the set of associated regression function values associated with the set of time offset values may be within a range from the corresponding extremum of the regression function in the regression window.

The searching for a local extremum may comprise robust search, minimization, maximization, optimization, statistical optimization, dual optimization, constraint optimization, convex optimization, global optimization, local optimization an energy minimization, linear regression, quadratic regression, higher order regression, linear programming, nonlinear programming, stochastic programming, combinatorial optimization, constraint programming, constraint satisfaction, calculus of variations, optimal control, dynamic programming, mathematical programming, multi-objective optimization, multi-modal optimization, disjunctive programming, space mapping, infinite-dimensional optimization, heuristics, metaheuristics, convex programming, semidefinite programming, conic programming, cone programming, integer programming, quadratic programming, fractional programming, numerical analysis, simplex algorithm, iterative method, gradient descent, subgradient method, coordinate descent, conjugate gradient method, Newton’s algorithm, sequential quadratic programming, interior point method, ellipsoid method, reduced gradient method, quasi-Newton method, simultaneous perturbation stochastic approximation, interpolation method, pattern search method, line search, non-differentiable optimization, genetic algorithm, evolutionary algorithm, dynamic relaxation, hill climbing, particle swarm optimization, gravitation search algorithm, simulated annealing, memetic algorithm, differential evolution, dynamic relaxation, stochastic tunneling, Tabu search, reactive search optimization, curve fitting, least square, simulation based optimization, variational calculus, and/or variant. The search for local extremum may be associated



with an objective function, loss function, cost function, utility function, fitness function, energy function, and/or an energy function.

Regression may be performed using regression function to fit sampled data (e.g. CI, feature of CI, component of CI) or another function (e.g. autocorrelation function) in a regression window. In at least one iteration, a length of the regression window and/or a location of the regression window may change. The regression function may be linear function, quadratic function, cubic function, polynomial function, and/or another function.

The regression analysis may minimize at least one of: error, aggregate error, component error, error in projection domain, error in selected axes, error in selected orthogonal axes, absolute error, square error, absolute deviation, square deviation, higher order error (e.g. third order, fourth order), robust error (e.g. square error for smaller error magnitude and absolute error for larger error magnitude, or first kind of error for smaller error magnitude and second kind of error for larger error magnitude), another error, weighted sum (or weighted mean) of absolute/square error (e.g. for wireless transmitter with multiple antennas and wireless receiver with multiple antennas, each pair of transmitter antenna and receiver antenna form a link), mean absolute error, mean square error, mean absolute deviation, and/or mean square deviation. Error associated with different links may have different weights. One possibility is that some links and/or some components with larger noise or lower signal quality metric may have smaller or bigger weight.), weighted sum of square error, weighted sum of higher order error, weighted sum of robust error, weighted sum of the another error, absolute cost, square cost, higher order cost, robust cost, another cost, weighted sum of absolute cost, weighted sum of square cost, weighted sum of higher order cost, weighted sum of robust cost, and/or weighted sum of another cost.

The regression error determined may be an absolute error, square error, higher order error, robust error, yet another error, weighted sum of absolute error, weighted sum of square error, weighted sum of higher order error, weighted sum of robust error, and/or weighted sum of the yet another error.

The time offset associated with maximum regression error (or minimum regression error) of the regression function with respect to the particular function in the regression window may become the updated current time offset in the iteration.

A local extremum may be searched based on a quantity comprising a difference of two different errors (e.g. a difference between absolute error and square error). Each of the two different errors may comprise an absolute error, square error, higher order error, robust error, another error, weighted sum of absolute error, weighted sum of square error, weighted sum of higher order error, weighted sum of robust error, and/or weighted sum of the another error.

The quantity may be compared with a reference data or a reference distribution, such as an F-distribution, central F-distribution, another statistical distribution, threshold, threshold associated with probability/histogram, threshold associated with probability/histogram of finding false peak, threshold associated with the F-distribution, threshold associated the central F-distribution, and/or threshold associated with the another statistical distribution.

The regression window may be determined based on at least one of: the movement (e.g. change in position/location) of the object, quantity associated with the object, the at least one characteristics and/or STI of the object associated with

the movement of the object, estimated location of the local extremum, noise characteristics, estimated noise characteristics, signal quality metric, F-distribution, central F-distribution, another statistical distribution, threshold, preset threshold, threshold associated with probability/histogram, threshold associated with desired probability, threshold associated with probability of finding false peak, threshold associated with the F-distribution, threshold associated the central F-distribution, threshold associated with the another statistical distribution, condition that quantity at the window center is largest within the regression window, condition that the quantity at the window center is largest within the regression window, condition that there is only one of the local extremum of the particular function for the particular value of the first time in the regression window, another regression window, and/or another condition.

The width of the regression window may be determined based on the particular local extremum to be searched. The local extremum may comprise first local maximum, second local maximum, higher order local maximum, first local maximum with positive time offset value, second local maximum with positive time offset value, higher local maximum with positive time offset value, first local maximum with negative time offset value, second local maximum with negative time offset value, higher local maximum with negative time offset value, first local minimum, second local minimum, higher local minimum, first local minimum with positive time offset value, second local minimum with positive time offset value, higher local minimum with positive time offset value, first local minimum with negative time offset value, second local minimum with negative time offset value, higher local minimum with negative time offset value, first local extremum, second local extremum, higher local extremum, first local extremum with positive time offset value, second local extremum with positive time offset value, higher local extremum with positive time offset value, first local extremum with negative time offset value, second local extremum with negative time offset value, and/or higher local extremum with negative time offset value.

A current parameter (e.g. time offset value) may be initialized based on a target value, target profile, trend, past trend, current trend, target speed, speed profile, target speed profile, past speed trend, the motion or movement (e.g. change in position/location) of the object, at least one characteristics and/or STI of the object associated with the movement of object, positional quantity of the object, initial speed of the object associated with the movement of the object, predefined value, initial width of the regression window, time duration, value based on carrier frequency of the signal, value based on subcarrier frequency of the signal, bandwidth of the signal, amount of antennas associated with the channel, noise characteristics, signal h metric, and/or an adaptive (and/or dynamically adjusted) value. The current time offset may be at the center, on the left side, on the right side, and/or at another fixed relative location, of the regression window.

In the presentation, information may be displayed with a map (or environmental model) of the venue. The information may comprise: location, zone, region, area, coverage area, corrected location, approximate location, location with respect to (w.r.t.) a map of the venue, location w.r.t. a segmentation of the venue, direction, path, path w.r.t. the map and/or the segmentation, trace (e.g. location within a time window such as the past 5 seconds, or past 10 seconds; the time window duration may be adjusted adaptively (and/or dynamically); the time window duration may be adaptively (and/or dynamically) adjusted w.r.t. speed, accelera-



tion, etc.), history of a path, approximate regions/zones along a path, history/summary of past locations, history of past locations of interest, frequently-visited areas, customer traffic, crowd distribution, crowd behavior, crowd control information, speed, acceleration, motion statistics, breathing rate, heart rate, presence/absence of motion, presence/absence of people or pets or object, presence/absence of vital sign, gesture, gesture control (control of devices using gesture), location-based gesture control, information of a location-based operation, identity (ID) or identifier of the respect object (e.g. pet, person, self-guided machine/device, vehicle, drone, car, boat, bicycle, self-guided vehicle, machine with fan, air-conditioner, TV, machine with movable part), identification of a user (e.g. person), information of the user, location/speed/acceleration/direction/motion/gesture/gesture control/motion trace of the user, ID or identifier of the user, activity of the user, state of the user, sleeping/resting characteristics of the user, emotional state of the user, vital sign of the user, environment information of the venue, weather information of the venue, earthquake, explosion, storm, rain, fire, temperature, collision, impact, vibration, event, door-open event, door-close event, window-open event, window-close event, fall-down event, burning event, freezing event, water-related event, wind-related event, air-movement event, accident event, pseudo-periodic event (e.g. running on treadmill, jumping up and down, skipping rope, somersault, etc.), repeated event, crowd event, vehicle event, gesture of the user (e.g. hand gesture, arm gesture, foot gesture, leg gesture, body gesture, head gesture, face gesture, mouth gesture, eye gesture, etc.).

The location may be 2-dimensional (e.g. with 2D coordinates), 3-dimensional (e.g. with 3D coordinates). The location may be relative (e.g. w.r.t. a map or environmental model) or relational (e.g. halfway between point A and point B, around a corner, up the stairs, on top of table, at the ceiling, on the floor, on a sofa, close to point A, a distance R from point A, within a radius of R from point A, etc.). The location may be expressed in rectangular coordinate, polar coordinate, and/or another representation.

The information (e.g. location) may be marked with at least one symbol. The symbol may be time varying. The symbol may be flashing and/or pulsating with or without changing color/intensity. The size may change over time. The orientation of the symbol may change over time. The symbol may be a number that reflects an instantaneous quantity (e.g. vital sign/breathing rate/heart rate/gesture/state/status/action/motion of a user, temperature, network traffic, network connectivity, status of a device/machine, remaining power of a device, status of the device, etc.). The rate of change, the size, the orientation, the color, the intensity and/or the symbol may reflect the respective motion. The information may be presented visually and/or described verbally (e.g. using pre-recorded voice, or voice synthesis). The information may be described in text. The information may also be presented in a mechanical way (e.g. an animated gadget, a movement of a movable part).

The user-interface (UI) device may be a smart phone (e.g. iPhone, Android phone), tablet (e.g. iPad), laptop (e.g. notebook computer), personal computer (PC), device with graphical user interface (GUI), smart speaker, device with voice/audio/speaker capability, virtual reality (VR) device, augmented reality (AR) device, smart car, display in the car, voice assistant, voice assistant in a car, etc.

The map (or environmental model) may be 2-dimensional, 3-dimensional and/or higher-dimensional. (e.g. a time varying 2D/3D map/environmental model) Walls, windows, doors, entrances, exits, forbidden areas may be

marked on the map or the model. The map may comprise floor plan of a facility. The map or model may have one or more layers (overlays). The map/model may be a maintenance map/model comprising water pipes, gas pipes, wiring, cabling, air ducts, crawl-space, ceiling layout, and/or underground layout. The venue may be segmented/subdivided/zoned/grouped into multiple zones/regions/geographic regions/sectors/sections/territories/districts/precincts/localities/neighborhoods/areas/stretches/expanse such as bedroom, living room, storage room, walkway, kitchen, dining room, foyer, garage, first floor, second floor, rest room, offices, conference room, reception area, various office areas, various warehouse regions, various facility areas, etc. The segments/regions/areas may be presented in a map/model. Different regions may be color-coded. Different regions may be presented with a characteristic (e.g. color, brightness, color intensity, texture, animation, flashing, flashing rate, etc.). Logical segmentation of the venue may be done using the at least one heterogeneous Type 2 device, or a server (e.g. hub device), or a cloud server, etc.

Here is an example of the disclosed system, apparatus, and method. Stephen and his family want to install the disclosed wireless motion detection system to detect motion in their 2000 sqft two-storey town house in Seattle, Wash. Because his house has two storeys, Stephen decided to use one Type 2 device (named A) and two Type 1 devices (named B and C) in the ground floor. His ground floor has predominantly three rooms: kitchen, dining room and living room arranged in a straight line, with the dining room in the middle. The kitchen and the living rooms are on opposite end of the house. He put the Type 2 device (A) in the dining room, and put one Type 1 device (B) in the kitchen and the other Type 1 device (C) in the living room. With this placement of the devices, he is practically partitioning the ground floor into 3 zones (dining room, living room and kitchen) using the motion detection system. When motion is detected by the AB pair and the AC pair, the system would analyze the motion information and associate the motion with one of the 3 zones.

When Stephen and his family go out on weekends (e.g. to go for a camp during a long weekend), Stephen would use a mobile phone app (e.g. Android phone app or iPhone app) to turn on the motion detection system. When the system detects motion, a warning signal is sent to Stephen (e.g. an SMS text message, an email, a push message to the mobile phone app, etc.). If Stephen pays a monthly fee (e.g. \$10/month), a service company (e.g. security company) will receive the warning signal through wired network (e.g. broadband) or wireless network (e.g. home WiFi, LTE, 3G, 2.5G, etc.) and perform a security procedure for Stephen (e.g. call him to verify any problem, send someone to check on the house, contact the police on behalf of Stephen, etc.). Stephen loves his aging mother and cares about her well-being when she is alone in the house. When the mother is alone in the house while the rest of the family is out (e.g. go to work, or shopping, or go on vacation), Stephen would turn on the motion detection system using his mobile app to ensure the mother is ok. He then uses the mobile app to monitor his mother's movement in the house. When Stephen uses the mobile app to see that the mother is moving around the house among the 3 regions, according to her daily routine, Stephen knows that his mother is doing ok. Stephen is thankful that the motion detection system can help him monitor his mother's well-being while he is away from the house.

On a typical day, the mother would wake up at around 7 AM. She would cook her breakfast in the kitchen for about



20 minutes. Then she would eat the breakfast in the dining room for about 30 minutes. Then she would do her daily exercise in the living room, before sitting down on the sofa in the living room to watch her favorite TV show. The motion detection system enables Stephen to see the timing of the movement in each of the 3 regions of the house. When the motion agrees with the daily routine, Stephen knows roughly that the mother should be doing fine. But when the motion pattern appears abnormal (e.g. there is no motion until 10 AM, or she stayed in the kitchen for too long, or she remains motionless for too long, etc.), Stephen suspects something is wrong and would call the mother to check on her. Stephen may even get someone (e.g. a family member, a neighbor, a paid personnel, a friend, a social worker, a service provider) to check on his mother.

At some time, Stephen feels like repositioning the Type 2 device. He simply unplugs the device from the original AC power plug and plug it into another AC power plug. He is happy that the wireless motion detection system is plug-and-play and the repositioning does not affect the operation of the system. Upon powering up, it works right away.

Sometime later, Stephen is convinced that our wireless motion detection system can really detect motion with very high accuracy and very low alarm, and he really can use the mobile app to monitor the motion in the ground floor. He decides to install a similar setup (i.e. one Type 2 device and two Type 1 devices) in the second floor to monitor the bedrooms in the second floor. Once again, he finds that the system set up is extremely easy as he simply needs to plug the Type 2 device and the Type 1 devices into the AC power plug in the second floor. No special installation is needed. And he can use the same mobile app to monitor motion in the ground floor and the second floor. Each Type 2 device in the ground floor/second floor can interact with all the Type 1 devices in both the ground floor and the second floor. Stephen is happy to see that, as he doubles his investment in the Type 1 and Type 2 devices, he has more than double the capability of the combined systems.

According to various embodiments, each CI (CI) may comprise at least one of: channel state information (CSI), frequency domain CSI, frequency representation of CSI, frequency domain CSI associated with at least one sub-band, time domain CSI, CSI in domain, channel response, estimated channel response, channel impulse response (CIR), channel frequency response (CFR), channel characteristics, channel filter response, CSI of the wireless multipath channel, information of the wireless multipath channel, timestamp, auxiliary information, data, meta data, user data, account data, access data, security data, session data, status data, supervisory data, household data, identity (ID), identifier, device data, network data, neighborhood data, environment data, real-time data, sensor data, stored data, encrypted data, compressed data, protected data, and/or another CI. In one embodiment, the disclosed system has hardware components (e.g. wireless transmitter/receiver with antenna, analog circuitry, power supply, processor, memory) and corresponding software components. According to various embodiments of the present teaching, the disclosed system includes Bot (referred to as a Type 1 device) and Origin (referred to as a Type 2 device) for vital sign detection and monitoring. Each device comprises a transceiver, a processor and a memory.

The disclosed system can be applied in many cases. In one example, the Type 1 device (transmitter) may be a small WiFi-enabled device resting on the table. It may also be a WiFi-enabled television (TV), set-top box (STB), a smart speaker (e.g. Amazon echo), a smart refrigerator, a smart

microwave oven, a mesh network router, a mesh network satellite, a smart phone, a computer, a tablet, a smart plug, etc. In one example, the Type 2 (receiver) may be a WiFi-enabled device resting on the table. It may also be a WiFi-enabled television (TV), set-top box (STB), a smart speaker (e.g. Amazon echo), a smart refrigerator, a smart microwave oven, a mesh network router, a mesh network satellite, a smart phone, a computer, a tablet, a smart plug, etc. The Type 1 device and Type 2 devices may be placed in/near a conference room to count people. The Type 1 device and Type 2 devices may be in a well-being monitoring system for older adults to monitor their daily activities and any sign of symptoms (e.g. dementia, Alzheimer's disease). The Type 1 device and Type 2 device may be used in baby monitors to monitor the vital signs (breathing) of a living baby. The Type 1 device and Type 2 devices may be placed in bedrooms to monitor quality of sleep and any sleep apnea. The Type 1 device and Type 2 devices may be placed in cars to monitor well-being of passengers and driver, detect any sleeping of driver and detect any babies left in a car. The Type 1 device and Type 2 devices may be used in logistics to prevent human trafficking by monitoring any human hidden in trucks and containers. The Type 1 device and Type 2 devices may be deployed by emergency service at disaster area to search for trapped victims in debris. The Type 1 device and Type 2 devices may be deployed in an area to detect breathing of any intruders. There are numerous applications of wireless breathing monitoring without wearables.

Hardware modules may be constructed to contain the Type 1 transceiver and/or the Type 2 transceiver. The hardware modules may be sold to/used by variable brands to design, build and sell final commercial products. Products using the disclosed system and/or method may be home/office security products, sleep monitoring products, WiFi products, mesh products, TV, STB, entertainment system, HiFi, speaker, home appliance, lamps, stoves, oven, microwave oven, table, chair, bed, shelves, tools, utensils, torches, vacuum cleaner, smoke detector, sofa, piano, fan, door, window, door/window handle, locks, smoke detectors, car accessories, computing devices, office devices, air conditioner, heater, pipes, connectors, surveillance camera, access point, computing devices, mobile devices, LTE devices, 3G/4G/5G/6G devices, UNITS devices, 3GPP devices, GSM devices, EDGE devices, TDMA devices, FDMA devices, CDMA devices, WCDMA devices, TD-SCDMA devices, gaming devices, eyeglasses, glass panels, VR goggles, necklace, watch, waist band, belt, wallet, pen, hat, wearables, implantable device, tags, parking tickets, smart phones, etc.

The summary may comprise: analytics, output response, selected time window, subsampling, transform, and/or projection. The presenting may comprise presenting at least one of: monthly/weekly/daily view, simplified/detailed view, cross-sectional view, small/large form-factor view, color-coded view, comparative view, summary view, animation, web view, voice announcement, and another presentation related to the periodic/repetition characteristics of the repeating motion.

A Type 1/Type 2 device may be an antenna, a device with antenna, a device with a housing (e.g. for radio, antenna, data/signal processing unit, wireless IC, circuits), device that has interface to attach/connect to/link antenna, device that is interfaced to/attached to/connected to/linked to another device/system/computer/phone/network/data aggregator, device with a user interface(UI)/graphical UI/display, device with wireless transceiver, device with wireless transmitter, device with wireless receiver, internet-of-thing (IoT) device,



device with wireless network, device with both wired networking and wireless networking capability, device with wireless integrated circuit (IC), Wi-Fi device, device with Wi-Fi chip (e.g. 802.11a/b/g/n/ac/ax standard compliant), Wi-Fi access point (AP), Wi-Fi client, Wi-Fi router, Wi-Fi repeater, Wi-Fi hub, Wi-Fi mesh network router/hub/AP, wireless mesh network router, adhoc network device, wireless mesh network device, mobile device (e.g. 2G/2.5G/3G/3.5G/4G/LTE/5G/6G/7G, UMTS, 3GPP, GSM, EDGE, TDMA, FDMA, CDMA, WCDMA, TD-SCDMA), cellular device, base station, mobile network base station, mobile network hub, mobile network compatible device, LTE device, device with LTE module, mobile module (e.g. circuit board with mobile-enabling chip (IC) such as Wi-Fi chip, LTE chip, BLE chip), Wi-Fi chip (IC), LTE chip, BLE chip, device with mobile module, smart phone, companion device (e.g. dongle, attachment, plugin) for smart phones, dedicated device, plug-in device, AC-powered device, battery-powered device, device with processor/memory/set of instructions, smart device/gadget/items: clock, stationary, pen, user-interface, paper, mat, camera, television (TV), set-top-box, microphone, speaker, refrigerator, oven, machine, phone, wallet, furniture, door, window, ceiling, floor, wall, table, chair, bed, night-stand, air-conditioner, heater, pipe, duct, cable, carpet, decoration, gadget, USB device, plug, dongle, lamp/light, tile, ornament, bottle, vehicle, car, AGV, drone, robot, laptop, tablet, computer, harddisk, network card, instrument, racket, ball, shoe, wearable, clothing, glasses, hat, necklace, food, pill, small device that moves in the body of creature (e.g. in blood vessels, in lymph fluid, digestive system), and/or another device. The Type 1 device and/or Type 2 device may be communicatively coupled with: the internet, another device with access to internet (e.g. smart phone), cloud server (e.g. hub device), edge server, local server, and/or storage. The Type 1 device and/or the Type 2 device may operate with local control, can be controlled by another device via a wired/wireless connection, can operate automatically, or can be controlled by a central system that is remote (e.g. away from home).

In one embodiment, a Type B device may be a transceiver that may perform as both Origin (a Type 2 device, a Rx device) and Bot (a Type 1 device, a Tx device), i.e., a Type B device may be both Type 1 (Tx) and Type 2 (Rx) devices (e.g. simultaneously or alternately), for example, mesh devices, a mesh router, etc. In one embodiment, a Type A device may be a transceiver that may only function as Bot (a Tx device), i.e., Type 1 device only or Tx only, e.g., simple IoT devices. It may have the capability of Origin (Type 2 device, Rx device), but somehow it is functioning only as Bot in the embodiment. All the Type A and Type B devices form a tree structure. The root may be a Type B device with network (e.g. internet) access. For example, it may be connected to broadband service through a wired connection (e.g. Ethernet, cable modem, ADSL/HDSL modem) connection or a wireless connection (e.g. LTE, 3G/4G/5G, WiFi, Bluetooth, microwave link, satellite link, etc.). In one embodiment, all the Type A devices are leaf node. Each Type B device may be the root node, non-leaf node, or leaf node.

Type 1 device (transmitter, or Tx) and Type 2 device (receiver, or Rx) may be on same device (e.g. RF chip/IC) or simply the same device. The devices may operate at high frequency band, such as 28 GHz, 60 GHz, 77 GHz, etc. The RF chip may have dedicated Tx antennas (e.g. 32 antennas) and dedicated Rx antennas (e.g. another 32 antennas).

One Tx antenna may transmit a wireless signal (e.g. a series of probe signal, perhaps at 100 Hz). Alternatively, all

Tx antennas may be used to transmit the wireless signal with beamforming (in Tx), such that the wireless signal is focused in certain direction (e.g. for energy efficiency or boosting the signal to noise ratio in that direction, or low power operation when “scanning” that direction, or low power operation if object is known to be in that direction).

The wireless signal hits an object (e.g. a living human lying on a bed 4 feet away from the Tx/Rx antennas, with breathing and heart beat) in a venue (e.g. a room). The object motion (e.g. lung movement according to breathing rate, or blood-vessel movement according to heart beat) may impact/modulate the wireless signal. All Rx antennas may be used to receive the wireless signal.

Beamforming (in Rx and/or Tx) may be applied (digitally) to “scan” different directions. Many directions can be scanned or monitored simultaneously. With beamforming, “sectors” (e.g. directions, orientations, bearings, zones, regions, segments) may be defined related to the Type 2 device (e.g. relative to center location of antenna array). For each probe signal (e.g. a pulse, an ACK, a control packet, etc.), a channel information or CI (e.g. channel impulse response/CIR, CSI, CFR) is obtained/computed for each sector (e.g. from the RF chip). In breathing detection, one may collect CIR in a sliding window (e.g. 30 sec, and with 100 Hz sounding/probing rate, one may have 3000 CIR over 30 sec).

The CIR may have many taps (e.g. N1 components/taps). In the present teaching, the terms “tap” and “tab” are used interchangeably herein to refer to a channel tap of a CIR. Each tap may be associated with a time lag, or a time-of-flight (tof, e.g. time to hit the human 4 feet away and back). When a person is breathing in a certain direction at a certain distance (e.g. 4 ft), one may search for the CIR in the “certain direction”. Then one may search for the tap corresponding to the “certain distance”. Then one may compute the breathing rate and heart rate from that tap of that CIR.

One may consider each tap in the sliding window (e.g. 30 second window of “component time series”) as a time function (e.g. a “tap function”, the “component time series”). One may examine each tap function in search of a strong periodic behavior (e.g. corresponds to breathing, perhaps in the range of 10 bpm to 40 bpm).

The Type 1 device and/or the Type 2 device may have external connections/links and/or internal connections/links. The external connections (e.g. connection **1110**) may be associated with 2G/2.5G/3G/3.5G/4G/LTE/5G/6G/7G/NB-IoT, UWB, WiMax, Zigbee, 802.16 etc. The internal connections (e.g., 1114A and 1114B, 1116, 1118, 1120) may be associated with WiFi, an IEEE 802.11 standard, 802.11a/b/g/n/ac/ad/af/ag/ah/ai/aj/aq/ax/ay, Bluetooth, Bluetooth 1.0/1.1/1.2/2.0/2.1/3.0/4.0/4.1/4.2/5, BLE, mesh network, an IEEE 802.16/1/1a/1b/2/2a/a/b/c/d/e/f/g/h/i/j/k/l/m/n/o/p/standard.

The Type 1 device and/or Type 2 device may be powered by battery (e.g. AA battery, AAA battery, coin cell battery, button cell battery, miniature battery, bank of batteries, power bank, car battery, hybrid battery, vehicle battery, container battery, non-rechargeable battery, rechargeable battery, NiCd battery, NiMH battery, Lithium ion battery, Zinc carbon battery, Zinc chloride battery, lead acid battery, alkaline battery, battery with wireless charger, smart battery, solar battery, boat battery, plane battery, other battery, temporary energy storage device, capacitor, fly wheel).

Any device may be powered by DC or direct current (e.g. from battery as described above, power generator, power convertor, solar panel, rectifier, DC-DC converter, with various voltages such as 1.2V, 1.5V, 3V, 5V, 6V, 9V, 12V,



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24V, 40V, 42V, 48V, 110V, 220V, 380V, etc.) and may thus have a DC connector or a connector with at least one pin for DC power.

Any device may be powered by AC or alternating current (e.g. wall socket in a home, transformer, inverter, shore-power, with various voltages such as 100V, 110V, 120V, 100-127V, 200V, 220V, 230V, 240V, 220-240V, 100-240V, 250V, 380V, 50 Hz, 60 Hz, etc.) and thus may have an AC connector or a connector with at least one pin for AC power. The Type 1 device and/or the Type 2 device may be positioned (e.g. installed, placed, moved to) in the venue or outside the venue.

For example, in a vehicle (e.g. a car, truck, lorry, bus, special vehicle, tractor, digger, excavator, teleporter, bulldozer, crane, forklift, electric trolley, AGV, emergency vehicle, freight, wagon, trailer, container, boat, ferry, ship, submersible, airplane, air-ship, lift, mono-rail, train, tram, rail-vehicle, railcar, etc.), the Type 1 device and/or Type 2 device may be an embedded device embedded in the vehicle, or an add-on device (e.g. aftermarket device) plugged into a port in the vehicle (e.g. OBD port/socket, USB port/socket, accessory port/socket, 12V auxiliary power outlet, and/or 12V cigarette lighter port/socket).

For example, one device (e.g. Type 2 device) may be plugged into 12V cigarette lighter/accessory port or OBD port or the USB port (e.g. of a car/truck/vehicle) while the other device (e.g. Type 1 device) may be plugged into 12V cigarette lighter/accessory port or the OBD port or the USB port. The OBD port and/or USB port can provide power, signaling and/or network (of the car/truck/vehicle). The two devices may jointly monitor the passengers including children/babies in the car. They may be used to count the passengers, recognize the driver, detect presence of passenger in a particular seat/position in the vehicle.

In another example, one device may be plugged into 12V cigarette lighter/accessory port or OBD port or the USB port of a car/truck/vehicle while the other device may be plugged into 12V cigarette lighter/accessory port or OBD port or the USB port of another car/truck/vehicle.

In another example, there may be many devices of the same type A (e.g. Type 1 or Type 2) in many heterogeneous vehicles/portable devices/smart gadgets (e.g. automated guided vehicle/AGV, shopping/luggage/moving cart, parking ticket, golf cart, bicycle, smart phone, tablet, camera, recording device, smart watch, roller skate, shoes, jackets, goggle, hat, eye-wear, wearable, Segway, scooter, luggage tag, cleaning machine, vacuum cleaner, pet tag/collar/wearable/implant), each device either plugged into 12V accessory port/OBD port/USB port of a vehicle or embedded in a vehicle. There may be one or more device of the other type B (e.g. B is Type 1 if A is Type 2, or B is Type 2 if A is Type 1) installed at locations such as gas stations, street lamp post, street corners, tunnels, multi-storey parking facility, scattered locations to cover a big area such as factory/stadium/train station/shopping mall/construction site. The Type A device may be located, tracked or monitored based on the TSCI.

The area/venue may have no local connectivity, e.g., broadband services, WiFi, etc. The Type 1 and/or Type 2 device may be portable. The Type 1 and/or Type 2 device may support plug and play.

Pairwise wireless links may be established between many pairs of devices, forming the tree structure. In each pair (and the associated link), a device (second device) may be a non-leaf (Type B). The other device (first device) may be a leaf (Type A or Type B) or non-leaf (Type B). In the link, the first device functions as a bot (Type 1 device or a Tx device)

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to send a wireless signal (e.g. probe signal) through the wireless multipath channel to the second device. The second device may function as an Origin (Type 2 device or Rx device) to receive the wireless signal, obtain the TSCI and compute a "linkwise analytics" based on the TSCI.

FIG. 1A illustrates an exemplary environment for wireless material sensing, according to some embodiments of the present disclosure. For example, as shown in FIG. 1A, in a 2-bedroom apartment 100, Origin 132 may be placed in the living-room area 102, while Bot 131 may be placed in the dining-room area 106. In this example, the Origin 132 and the Bot 131 are in two separate devices, while there is a line-of-sight (LOS) between the Origin 132 and the Bot 131, when they cooperate to perform wireless material sensing as a Bot-Origin pair.

In another example, as shown in FIG. 1A, a device 120 including both a Bot 121 and an Origin 122 is placed in a bedroom1-area 104. In this example, the Origin 122 and the Bot 121 are located next to each other on the device 120, when they cooperate to perform wireless material sensing as a Bot-Origin pair.

In yet another example, as shown in FIG. 1A, a device 110 including both a Bot 111 and an Origin 112 is placed in a bedroom2-area 108. In this example, the Origin 112 and the Bot 111 are located far apart from each other on the device 110 with a LOS between them, when they cooperate to perform wireless material sensing as a Bot-Origin pair.

Each Bot of a Bot-Origin pair can transmit a wireless signal through a wireless multipath channel, while a corresponding Origin of the pair can obtain channel information of the wireless multipath channel based on the wireless signal. As the wireless signal may experience reflection by a surface of a material of an object after being transmitted by the Bot and before being received by the Origin, the channel information obtained by the Origin somehow includes information related to the type of the material. For example, the Origin, by itself or through a third device like a material detector, can compute material feature information based on the channel information and detect the type of the material based on the material feature information.

FIG. 1B illustrates an exemplary scenario for wireless material sensing, according to some embodiments of the present disclosure. The wireless material sensing shown in FIG. 1B is performed by the device 110 having both the Bot 111 and the Origin 112. As shown in FIG. 1B, the Bot 111 and the Origin 112 are in LOS of each other, and there is a LOS distance D1 between them. Although each of the Bot 111 and the Origin 112 may have both transmitter and receiver, in this example, the Bot 111 serves as a transmitter (including one or more transmit antennas) and the Origin 112 serves as a receiver (including one or more receive antennas). The Bot 111 may transmit a wireless signal 114, which is reflected by a surface of an object 115. The object 115 may be a wall, a piece of furniture, a device, a person, an animal, etc. The surface material of the object 115 may impact the wireless signal 114, such that the reflected wireless signal 116 after the reflection at the surface can include information related to the type of the surface material. As such, after the Origin 112 receives the reflected wireless signal 116, the Origin 112 can compute or detect the type of the material of the object 115, based on the reflected wireless signal 116 and/or other context information. In some embodiments, the context information may include: the distance D1 between the Bot 111 and the Origin 112, and/or the distance D2 between the object 115 and the device 110 as shown in FIG. 1B.



In some embodiments of the present teaching, a mobile material sensing system (referred to as “mSense” hereinafter) using a single millimeter-wave (mmWave) radio is disclosed. Unlike existing systems that mostly rely on penetrating signals and/or multiple transceivers, mSense exploits the signals reflecting off the target and employs a single commodity mmWave networking radio. Different objects, depending on their specific materials, reflect the incident electromagnetic waves at distinct extents. For example, metals typically reflect much more energy than woods. The mSense system circumvents the need to put up two or more radios on both sides of the target or to instrument it with any device, and thus allows everyday usage in ubiquitous environments. To identify the target material, a user can simply point the radio towards the target, either holding it still or moving it for a short distance. The mSense system can then measure Channel Impulse Response (CIR) of the reflected signals and calculates a novel parameter from the extracted CIR to determine the material type, without involving any unexplainable features or machine learning.

In some embodiments, the mSense system models the signal propagation with the reflection coefficient, an intrinsic property of the material. The mSense system then derives a novel material reflection feature (MRF) that quantitatively characterizes the material’s reflectivity and accordingly associates the target’s material type. Being independent of the environments and the propagation distance, the MRF allows material identification in mobile contexts with flexible setup. To estimate the MRF precisely and reliably may entail various challenges in practice. Particularly, the CIR measured using an mmWave platform offers limited range resolution (4.26 cm given the bandwidth of 3.52 GHz), contains synchronization drifts, and suffers from significant measurement noises, all leading to errors in the estimation of the propagation distance and the signal amplitude. To overcome these challenges, the mSense system first upsamples the measured CIR to break down the range estimation precision to the sub-centimeter level. A novel synchronization scheme by leveraging the direct path, i.e., direct leakage between the co-located transmitter (Tx) and receiver (Rx), to synchronize all the CIRs is then presented. To combat the measurement noises, noise cancellation may be deployed to eliminate the hardware distortions and measurement noises and obtain the components that only relate to the target reflection. The spatial diversity attributed by the large antenna arrays to facilitate the robustness is further studied. Then target detection on the CIR is presented to estimate the accurate propagation distance and the corresponding amplitude response and accordingly calculate the MRF. Finally, the mSense system can directly determine the material type by looking up the best-matched record in a prior database with the estimated MRF value.

One may implement a prototype of the mSense system on a mmWave testbed, which enables radar-like operations on a commodity high frequency 802.11ad/ay chipset by attaching one additional antenna array, each including multiple (e.g. 32) antennas. One may conduct experiments using this testbed to validate the performance on several (e.g., 5) common types of materials: metal (aluminum), plastic, ceramic, water, wood. The results show that the mSense system achieves an average identification accuracy of 92.87%, regardless of the various target sizes, thicknesses, and distances to the device. More importantly, the accuracy retains 89.36% in mobile scenarios where a user holds and moves the device for sensing. Relying merely on the reflection signals measured by a mobile radio, the disclosed

system sheds light on ubiquitous material identification for everyday usage. The practice on the radar platform that reuses a networking device also takes a step towards joint radar communication systems, which may promise the future paradigm of wireless communication and sensing.

One may aim at mobile applications in ubiquitous contexts that demand the awareness of the material type of a target. For example, one may be interested in knowing the materials of daily objects, e.g., telling whether a whiteboard is made up of metal or plastic; a robot (e.g., a robot vacuum cleaner) can accordingly adapt its behavior according to the material types of surrounding objects. Next-generation educational toys and equipment could instruct kids to perceive the physical world in interactive ways. Novel applications like interactive input devices that change their functions based on the material it touches would also be enabled. Taking a further step, if the mmWave radio becomes available on smartphones, the mSense system will immediately offer the capability of a smartphone for daily material sensing. A key enabler to these applications is ubiquitous material sensing in mobile environments, without dedicated hardware or the cumbersome setup.

Specifically, one may envision the following usage scenarios: A user simply holds the portable radio and points the antenna array towards the target for a short instance, and the system will automatically recognize the material of the target. The user will be allowed to either hold the device still, or if he likes, move it towards the target. If a user chooses to move the radio, he/she generally can move it at will but only needs to keep the antennas as perpendicular as possible towards the target. The radar keeps transmitting signals and receiving reflection signals during the sensing period. From the series of the received signals, the mSense system will automatically determine its material type, independent of the environments, target sizes, and thicknesses, etc. While specialized devices have been explored for material recognition, in the present teaching, one may aim to leverage commodity wireless devices for a low-cost and portable solution. More specifically, the ultimate goal is to enable such capability on a smartphone or another smart device, should it be equipped with an mmWave radio in the future, to perform target material sensing everywhere.

The past years have seen an explosion in wireless sensing and tracking. Another trend, in the meanwhile, is the synergistic design of communication and radar systems that use the same hardware and spectral resources for dual functions of both wireless communication and radar sensing. Today, millimeter-wave radios have emerged as an increasingly popular technology for next-generation WiFi, as standardized as 802.11ad/ay. 60 GHz WiFi is already offered in commodity routers and is being integrated into smartphones and in vehicles. The same radio, with the large bandwidth and phased antenna array, is also promising for short-range radar applications. In addition to academic research, the industry is also actively exploring to enable radar-like capabilities like gesture recognition and room mapping by reusing the 60 GHz radios. The device can transmit and receive on a single 60 GHz chip and thus underpins radar-like features. Such a dual networking and radar device has distinct advantages compared to existing solutions since it reuses the networking device and will immediately become a ubiquitous radar on mobile devices when 60 GHz WiFi is widely deployed. In fact, it is no surprise that radar capability will go into smartphones in the near future. Operating a 60 GHz radio in a radar mode likely provides higher quality for material identification and other sensing applications compared to 2.4 GHz/5 GHz WiFi. The second



motivation for using 60 GHz radio is the design choice of using reflection signals only. A bottleneck preventing existing solutions from ubiquitous applications is that they require a special setup with two or more transceivers on both sides of the target or with a tag attached to the target. These devices are limited to be used at fixed locations and not yet ready to enable truly ubiquitous material sensing anywhere. In addition to the inconvenience, the use of penetrating signals imposes two fundamental issues. First, EM wave propagating in different medias (e.g., lossy media vs. lossless media) decays significantly differently. For example, in free space and approximately in air, the amplitude decreases linearly with respect to  $1/d$  where  $d$  is the propagation distance. Differently, in a lossy media, amplitude experiences exponential decrease over  $d$ . As a result, prior works either apply a universal model for different media present in the propagation path or assume a specific category of materials (particularly different liquids). The second issue is that for conductive materials (e.g., metals, graphite), RF signals may not be able to penetrate the target. Neither can wireless signals, especially those at mmWave frequency bands, penetrate very thick objects. In the present teaching, to overcome the limitations and improve usability, one may exploit only the reflection signals for analysis, hence avoiding a special two-sided setup as well as bypassing the model generality issue. The 60 GHz signals, with the large bandwidth and many antennas, offer better resolution in resolving the reflection signals.

Overall, the mSense system aims to achieve target material sensing from reflection signals by using one single 60 GHz device, which would promise ubiquitous usage in mobile environments. It is more challenging and somewhat indirect to use reflection signals for material sensing since the received signals have not passed through the material at all. The rationale is that different materials reflect the incoming signals at distinctly different extents and thus “encode” the material type information in the reflected signals.

FIG. 2 illustrates an exemplary workflow for wireless material sensing based on channel impulse response (CIR), according to some embodiments of the present disclosure. To be specific, FIG. 2 shows a method 200 of the mSense system for determining a material type based on a channel impulse response (CIR) obtained from a reflected wireless signal. As shown in FIG. 2, the mSense system’s operations include two stages: a training stage 210 that constructs a database 207 of different materials and a testing stage 220 that tests a target by matching against the database 207.

To determine or identify the material type at operation 208 in the testing stage 220, multiple operations may be performed to process the raw CIR. The mSense system may collect CIRs at operation 201. For example, the CIRs may be collected when the user points the radio towards a target object (e.g. roughly perpendicularly). Then a CIR interpolation is performed at operation 202. For example, the raw CIRs are upsampled to improve range accuracy. The time series of CIR measurements are then synchronized, at operation 203.

Then at operation 204, the system may employ noise cancellation to eliminate the hardware distortions and measurement noises. The system may then perform target detection at operation 205 to obtain the amplitudes and distances from all available antenna pairs, from which the system may estimate the Material Reflection Feature (MRF) at operation 206. In some embodiments, the MRF can characterize the material’s reflectivity and can be easily computed from reflection signals only. Finally, the system may determine

the material type at operation 208 by finding the best match against the pre-trained database 207 storing the MRF of different materials.

In some embodiments, the training and testing stages share the same processing procedure for MRF extraction and estimation, i.e. the operations 201-206 as shown in FIG. 2. The training only needs to be done once for each type of material and can be done under a different setting from the testing stage.

FIG. 3 illustrates an exemplary block diagram of a first wireless device, e.g. a Bot 300, of a wireless material sensing system, according to one embodiment of the present teaching. The Bot 300 is an example of a device or part of a device that can be configured to implement the various methods described herein. As shown in FIG. 3, the Bot 300 includes a housing 340 containing a processor 302, a memory 304, a transceiver 310 comprising a transmitter 312 and receiver 314, a synchronization controller 306, a power module 308, an optional carrier configurator 320 and a wireless signal generator 322.

In this embodiment, the processor 302 controls the general operation of the Bot 300 and can include one or more processing circuits or modules such as a central processing unit (CPU) and/or any combination of general-purpose microprocessors, microcontrollers, digital signal processors (DSPs), field programmable gate array (FPGAs), programmable logic devices (PLDs), controllers, state machines, gated logic, discrete hardware components, dedicated hardware finite state machines, or any other suitable circuits, devices and/or structures that can perform calculations or other manipulations of data.

The memory 304, which can include both read-only memory (ROM) and random access memory (RAM), can provide instructions and data to the processor 302. A portion of the memory 304 can also include non-volatile random access memory (NVRAM). The processor 302 typically performs logical and arithmetic operations based on program instructions stored within the memory 304. The instructions (a.k.a., software) stored in the memory 304 can be executed by the processor 302 to perform the methods described herein. The processor 302 and the memory 304 together form a processing system that stores and executes software. As used herein, “software” means any type of instructions, whether referred to as software, firmware, middleware, microcode, etc. which can configure a machine or device to perform one or more desired functions or processes. Instructions can include code (e.g., in source code format, binary code format, executable code format, or any other suitable format of code). The instructions, when executed by the one or more processors, cause the processing system to perform the various functions described herein.

The transceiver 310, which includes the transmitter 312 and receiver 314, allows the Bot 300 to transmit and receive data to and from a remote device (e.g., an Origin or another Bot). An antenna 350 is typically attached to the housing 340 and electrically coupled to the transceiver 310. In various embodiments, the Bot 300 includes (not shown) multiple transmitters, multiple receivers, and multiple transceivers. In one embodiment, the antenna 350 is replaced with a multi-antenna array 350 that can form a plurality of beams each of which points in a distinct direction. The transmitter 312 can be configured to wirelessly transmit signals having different types or functions, such signals being generated by the processor 302. Similarly, the receiver 314 is configured to



receive wireless signals having different types or functions, and the processor 302 is configured to process signals of a plurality of different types.

The Bot 300 in this example may serve as a Bot in FIG. 1A for detecting a material type of a surface of an object in a venue. For example, the wireless signal generator 322 may generate and transmit, via the transmitter 312, a wireless signal through a wireless multipath channel of the venue. The wireless signal carries information of the channel. Because the wireless signal is reflected at the surface of the object, the channel information includes MRF information of the object's surface material. As such, the material type can be indicated and detected based on the wireless signal. The generation of the wireless signal at the wireless signal generator 322 may be based on a request for material sensing from another device, e.g. an Origin, or based on a system pre-configuration. That is, the Bot 300 may or may not know that the wireless signal transmitted will be used for material sensing.

The synchronization controller 306 in this example may be configured to control the operations of the Bot 300 to be synchronized or un-synchronized with another device, e.g. an Origin or another Bot. In one embodiment, the synchronization controller 306 may control the Bot 300 to be synchronized with an Origin that receives the wireless signal transmitted by the Bot 300. In another embodiment, the synchronization controller 306 may control the Bot 300 to transmit the wireless signal asynchronously with other Bots. In another embodiment, each of the Bot 300 and other Bots may transmit the wireless signals individually and asynchronously.

The carrier configurator 320 is an optional component in Bot 300 to configure transmission resources, e.g. time and carrier, for transmitting the wireless signal generated by the wireless signal generator 322. In one embodiment, each CI of the time series of CI has one or more components each corresponding to a carrier or sub-carrier of the transmission of the wireless signal. The wireless material sensing may be based on any one or any combination of the components.

The power module 308 can include a power source such as one or more batteries, and a power regulator, to provide regulated power to each of the above-described modules in FIG. 3. In some embodiments, if the Bot 300 is coupled to a dedicated external power source (e.g., a wall electrical outlet), the power module 308 can include a transformer and a power regulator.

The various modules discussed above are coupled together by a bus system 330. The bus system 330 can include a data bus and, for example, a power bus, a control signal bus, and/or a status signal bus in addition to the data bus. It is understood that the modules of the Bot 300 can be operatively coupled to one another using any suitable techniques and mediums.

Although a number of separate modules or components are illustrated in FIG. 3, persons of ordinary skill in the art will understand that one or more of the modules can be combined or commonly implemented. For example, the processor 302 can implement not only the functionality described above with respect to the processor 302, but also implement the functionality described above with respect to the wireless signal generator 322. Conversely, each of the modules illustrated in FIG. 3 can be implemented using a plurality of separate components or elements.

FIG. 4 illustrates an exemplary block diagram of a second wireless device, e.g. an Origin 400, of a wireless material sensing system, according to one embodiment of the present teaching. The Origin 400 is an example of a device or part

of a device that can be configured to implement the various methods described herein. The Origin 400 in this example may serve as an Origin in FIG. 1A for wireless material sensing in a venue. As shown in FIG. 4, the Origin 400 includes a housing 440 containing a processor 402, a memory 404, a transceiver 410 comprising a transmitter 412 and a receiver 414, a power module 408, a synchronization controller 406, a channel information extractor 420, and an optional material detector 422.

In this embodiment, the processor 402, the memory 404, the transceiver 410 and the power module 408 work similarly to the processor 302, the memory 304, the transceiver 310 and the power module 308 in the Bot 300. An antenna 450 or a multi-antenna array 450 is typically attached to the housing 440 and electrically coupled to the transceiver 410.

In one embodiment, the Origin 400 may be a second wireless device that has a different type from that of the first wireless device (e.g. the Bot 300). In another embodiment, the Origin 400 and the Bot 300 are coupled to each other on a same device. The channel information extractor 420 in the Origin 400 is configured for receiving the wireless signal through the wireless multipath channel, and obtaining a plurality of channel information (CI) of the wireless multipath channel based on the wireless signal. The channel information extractor 420 may send the extracted CI to the optional material detector 422 or to a material detector outside the Origin 400 for detecting a material type in the venue.

The material detector 422 is an optional component in the Origin 400. In one embodiment, it is within the Origin 400 as shown in FIG. 4. In another embodiment, it is outside the Origin 400 and in another device, which may be a Bot, another Origin, a cloud server, a fog server, a local server, and an edge server. The optional material detector 422 may be configured for detecting a material of an object in the venue based on MRF information related to the material of the object. The MRF information is computed based on the plurality of CI by the material detector 422 or another material detector outside the Origin 400.

The synchronization controller 406 in this example may be configured to control the operations of the Origin 400 to be synchronized or un-synchronized with another device, e.g. a Bot, another Origin, or an independent motion detector. In one embodiment, the synchronization controller 406 may control the Origin 400 to be synchronized with a Bot that transmits a wireless signal. In another embodiment, the synchronization controller 406 may control the Origin 400 to receive the wireless signal asynchronously with other Origins. In another embodiment, each of the Origin 400 and other Origins may receive the wireless signals individually and asynchronously. In one embodiment, the optional material detector 422 or a material detector outside the Origin 400 is configured for asynchronously computing respective heterogeneous MRF information related to the material of the object based on the respective plurality of CI.

The various modules discussed above are coupled together by a bus system 430. The bus system 430 can include a data bus and, for example, a power bus, a control signal bus, and/or a status signal bus in addition to the data bus. It is understood that the modules of the Origin 400 can be operatively coupled to one another using any suitable techniques and mediums.

Although a number of separate modules or components are illustrated in FIG. 4, persons of ordinary skill in the art will understand that one or more of the modules can be combined or commonly implemented. For example, the processor 402 can implement not only the functionality



described above with respect to the processor 402, but also implement the functionality described above with respect to the channel information extractor 420. Conversely, each of the modules illustrated in FIG. 4 can be implemented using a plurality of separate components or elements.

FIG. 5 illustrates a flow chart of an exemplary method 500 for wireless material sensing, according to some embodiments of the present teaching. At operation 502, a first wireless signal is transmitted, by a plurality of transmit antennas of a transmitter, through a wireless multipath channel of a venue to a receiver. At operation 504, a second wireless signal is received, by a plurality of receive antennas of the receiver, through the wireless multipath channel. The second wireless signal comprises a reflection or a refraction of the first wireless signal at a surface of a target material of an object in the venue. At operation 506, a plurality of channel information (CI) of the wireless multipath channel is obtained based on the second wireless signal, e.g. using a processor, a memory communicatively coupled with the processor and a set of instructions stored in the memory. Each CI is associated with a respective one of the plurality of transmit antennas and associated with a respective one of the plurality of receive antennas. At operation 508, a material analytics is computed based on the plurality of CI. At operation 510, a type of the target material of the object is determined based on the material analytics. In some embodiments, the first wireless signal is a wireless probe signal. In some embodiments, each CI comprises at least one of: a channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI). The order of the operations in FIG. 5 may be changed according to various embodiments of the present teaching.

FIG. 6 illustrates a flow chart of an exemplary method 600 for CIR interpolation and CIR synchronization, according to some embodiments of the present disclosure. At operation 602, all CIRs are interpolated by an interpolation factor, based on at least one of: linear interpolation, polynomial interpolation or spline interpolation. At operation 604, all of the interpolated CIRs are synchronized by aligning the CIRs based on LOS tabs, wherein each of LOS tabs is a CIR tab with a magnitude corresponding to the LOS component of the wireless probe signal. At operation 606, the material analytics is computed based on the synchronized CIRs. The order of the operations in FIG. 6 may be changed according to various embodiments of the present teaching.

FIG. 7 illustrates a flow chart of an exemplary method 700 for CIR synchronization, according to some embodiments of the present disclosure. At operation 702, one of the CIRs is determined as a reference CIR. At operation 704, a reference window of tabs of the reference CIR encompassing at least one LOS tab is determined. At operation 706, a matching score is computed between the reference window of the reference CIR and a sliding window of an additional CIR to determine a best-matched sliding window with a maximum matching score. At operation 708, the additional CIR is aligned with the reference CIR based on the reference window and the best-matched sliding window. At operation 710, the additional CIR is rotated such that the best-matched sliding window is shifted to a same tab location as the reference window. The order of the operations in FIG. 7 may be changed according to various embodiments of the present teaching.

FIG. 8 illustrates a flow chart of another exemplary method 800 for CIR synchronization, according to some embodiments of the present disclosure. At operation 802, one of the CIRs is determined as a reference CIR. At

operation 804, a representative tab location of the reference CIR is computed. At operation 806, a representative tab location of an additional CIR is computed. At operation 808, the additional CIR is aligned with the reference CIR based on the representative tab locations of the reference CIR and the additional CIR. At operation 810, the additional CIR is rotated such that its representative tab location is closer to the representative tab location of the reference CIR. The order of the operations in FIG. 8 may be changed according to various embodiments of the present teaching.

FIG. 9 illustrates a flow chart of an exemplary method 900 for noise cancellation and target detection, according to some embodiments of the present disclosure. At operation 902, a respective background CIR is synchronized with a CIR (unprocessed). At operation 904, the synchronized background CIR is scaled. At operation 906, a respective background-subtracted CIR is computed by subtracting the scaled synchronized background CIR from the CIR. At operation 908, a spatial-temporal quantity is computed based on a respective background-subtracted CIR. At operation 909, it is determined whether there is any unprocessed CIR left. If so, the method goes back to operation 902 to perform noise cancellation regarding the unprocessed CIR. If not, the method goes to operation 910 to compute the material analytics based on the plurality of spatial-temporal quantities computed based on all of the CIRs. The order of the operations in FIG. 9 may be changed according to various embodiments of the present teaching.

FIG. 10 illustrates a flow chart of an exemplary method 1000 for obtaining background CIRs, according to some embodiments of the present disclosure. At operation 1002, an additional wireless probe signal is transmitted, by the plurality of transmit antennas of the transmitter, through the wireless multipath channel of the venue, with the object removed from a field of interest. At operation 1004, the additional wireless probe signal is received, by the plurality of receive antennas of the receiver, through the wireless multipath channel. At operation 1006, the plurality of background CIRs of the wireless multipath channel is obtained based on the additional wireless probe signal. Both a respective CIR and a respective background CIR subtracted from the respective CIR are associated with a same transmit antenna and a same receive antenna. The order of the operations in FIG. 10 may be changed according to various embodiments of the present teaching.

FIG. 11 illustrates a flow chart of another exemplary method 1100 for obtaining background CIRs, according to some embodiments of the present disclosure. At operation 1102, an additional wireless probe signal is transmitted, by the plurality of transmit antennas of the transmitter, through the wireless multipath channel of the venue, with the object removed from a field of interest. At operation 1104, the additional wireless probe signal is received, by the plurality of receive antennas of the receiver, through the wireless multipath channel. At operation 1106, a plurality of trial CIRs of the wireless multipath channel is obtained based on the additional wireless probe signal. At operation 1108, it is determined whether there is any object in the field of interest based on the plurality of trial CIRs to generate a determination result. If it is determined there is any object in the field of interest at operation 1109, the method goes back to operation 1102 to transmit another wireless probe signal to obtain background CIRs. If it is determined there is no object in the field of interest at operation 1109, the method goes to operation 1110 to obtain the plurality of background CIRs based on the plurality of trial CIRs automatically. The



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order of the operations in FIG. 11 may be changed according to various embodiments of the present teaching.

FIG. 12 illustrates a flow chart of an exemplary method 1200 for material reflection feature (MRF) estimation, according to some embodiments of the present disclosure. At operation 1202, a pair of transmit antenna and receive antenna is identified. At operation 1204, it is determined that a background-subtracted CIR is associated with the transmit antenna and the receive antenna, with a first CIR tab associated with the LOS component of the wireless probe signal. At operation 1206, a maximum magnitude of the background-subtracted CIR is identified after the first CIR tab, wherein the maximum magnitude is associated with a second CIR tab of the background-subtracted CIR. At operation 1208, a candidate material analytics is computed based on the second CIR tab and the maximum magnitude. At operation 1209, it is determined whether there is any more antenna pair. If so, the method goes back to operation 1202 to compute a candidate material analytics based on the next antenna pair. If not, the method goes to operation 1210 to compute the material analytics based on an aggregate analytics of the plurality of candidate material analytics computed based on all antenna pairs. The order of the operations in FIG. 12 may be changed according to various embodiments of the present teaching.

FIG. 13 illustrates a flow chart of another exemplary method 1300 for MRF estimation, according to some embodiments of the present disclosure. At operation 1302, a pair of transmit antenna and receive antenna is identified. At operation 1304, a first distance is determined between the transmit antenna and the receive antenna. At operation 1306, a time difference is computed between the first CIR tab and the second CIR tab, based on a sampling frequency of the background-subtracted CIR. At operation 1308, a second distance is computed based on a product of the time difference and a wave propagation speed of the wireless probe signal in the venue. At operation 1310, a third distance is computed based on a weighted sum of the first distance and the second distance. At operation 1312, a candidate material analytics is computed based on the maximum magnitude and the third distance. At operation 1313, it is determined whether there is any more antenna pair. If so, the method goes back to operation 1302 to compute a candidate material analytics based on the next antenna pair. If not, the method goes to operation 1314 to compute the material analytics based on an aggregate analytics of the plurality of candidate material analytics computed based on all antenna pairs. The order of the operations in FIG. 13 may be changed according to various embodiments of the present teaching.

FIG. 14 illustrates a flow chart of an exemplary method 1400 for wireless material sensing based on multiple frames, according to some embodiments of the present disclosure. At operation 1402, a third wireless signal is transmitted, by the plurality of transmit antennas of the transmitter, through the wireless multipath channel of the venue to the receiver. At operation 1404, a fourth wireless signal is received, by the plurality of receive antennas of the receiver, through the wireless multipath channel. The fourth wireless signal comprises a reflection or a refraction of the third wireless signal at the surface of the target material of the object in the venue. At operation 1406, a plurality of additional channel information (CI) of the wireless multipath channel is obtained based on the fourth wireless signal. Each additional CI is associated with a respective one of the plurality of transmit antennas and associated with a respective one of the plurality of receive antennas. At operation 1408, an additional material analytics is computed based on the plurality of additional CI. At operation 1410, an aggregate material analytics is computed based on the additional material analytics and the material analytics computed based on the

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method 500 in FIG. 5. At operation 1412, the type of the target material of the object is determined based on the aggregate material analytics. The order of the operations in FIG. 14 may be changed according to various embodiments of the present teaching.

FIG. 15 illustrates a flow chart of an exemplary method 1500 for training a classifier during a training stage of a wireless material sensing system, according to some embodiments of the present disclosure. At operation 1502, a first wireless training signal is transmitted, by a plurality of transmit antennas of a training transmitter, through a training wireless multipath channel of a training venue including a training target material to a training receiver. At operation 1504, a second wireless training signal is received, by a plurality of receive antennas of the training receiver, through the wireless multipath channel. The second wireless training signal comprises a reflection or a refraction of the first wireless training signal at a surface of the training target material. At operation 1506, a plurality of training channel information (CI) of the training wireless multipath channel is obtained based on the second wireless training signal. Each training CI is associated with a respective one of the plurality of transmit antennas and associated with a respective one of the plurality of receive antennas. At operation 1508, a training material analytics is computed based on the plurality of training CI. At operation 1509, it is determined whether there is any more training material. If so, the method goes back to operation 1502 to compute a training material analytics for the next based on the next training material. If not, the method goes to operation 1510 to train a classifier based on machine learning and all training material analytics. The order of the operations in FIG. 15 may be changed according to various embodiments of the present teaching.

For an EM wave propagating in free space, the signal amplitude decreases as the inverse of the propagation distance  $d$ , which is well modeled by the Friis Transmission Formula as:

$$A_d = A_0 g_t g_r \frac{\lambda}{4\pi d}, \quad (1)$$

where  $A_0$  denotes the amplitude of the transmitted signal,  $A_d$  denotes the received amplitude at propagation distance  $d$ ,  $g_t$  and  $g_r$  are the transmit and receive antenna gains, respectively, and  $\lambda$  is the wavelength. The model above generally applies to air propagation, which is approximated to free space propagation. In practice, due to multipath effects, an additional exponential component may be applied to  $d$ , which is not the case for 60 GHz signals with few multipath.

When the EM wave encounters a material boundary, causing an impedance discontinuity in the propagation medium, the incident energy will be partially reflected and partially transmitted into the new material. The ratio of the amplitude of the reflected wave to that of the incident wave is given by the reflection coefficient, denoted as  $r$ :

$$A_{out} = A_{in} r, \quad (2)$$

where  $A_{in}$  and  $A_{out}$  denote the amplitudes of the incoming and reflecting signals respectively. At normal incidence, the reflection coefficient  $r$  is, according to the Fresnel Equations, expressed as

$$r = \frac{n_2 - n_1}{n_2 + n_1},$$

where  $n_1$  and  $n_2$  are the refractive indices of the incident and transmitted materials, respectively. The refractive index  $n$  of



a material is defined as the ratio of the speed of light in vacuum,  $c$ , and the speed of EM waves in the propagation medium,  $v$ :

$$n = \frac{c}{v}.$$

The refractive index  $n$  is an intrinsic characteristic of a material related to the material's complex permittivity  $\epsilon_r = \epsilon'_r + j\epsilon''_r$ :

$$n = \sqrt{\frac{1}{2} \left( \sqrt{(\epsilon'_r)^2 + (\epsilon''_r)^2} + \epsilon'_r \right)}. \quad (3)$$

Typically, the incident material is air, for which we have  $n_{air} = 1$ . And thus  $r$  becomes  $r = (n-1)/(n+1)$ , where  $n$  denotes the refractive index of the target material.

For the EM wave that continues to travel inside the target, assuming a uniform lossy media, its amplitude experiences exponential decrease over the propagation distance  $d$ :

$$A_{d_{in}} = A_{in} e^{-\alpha d_{in}}, \quad (4)$$

where  $A_{d_{in}}$  denotes the amplitude at distance  $d_{in}$  to the target surface and  $A_{in}$  denotes the amplitude at the incident surface.  $\alpha$  is the attenuation constant that depends on the intrinsic material properties. From (4),  $\alpha$  is defined as the inverse of a distance  $\delta$ , often called the skin depth (or penetration depth), over which the strength of the electromagnetic field decays to  $1/e = 0.368$  of its original value.

Similar to the refractive index, the attenuation constant  $\alpha$  is also related to the material's intrinsic relative permittivity:

$$\alpha = \frac{2\pi}{\lambda_0} \sqrt{\frac{1}{2} \left( \sqrt{(\epsilon'_r)^2 + (\epsilon''_r)^2} - \epsilon'_r \right)}. \quad (5)$$

Thus, if  $n$  and  $\alpha$  are available, the above two equations can be jointly solved to derive the two unknowns, i.e.,  $\epsilon'_r$  and  $\epsilon''_r$ .

One may extract an effective metric related to the material's reflection behavior, termed as material reflection feature (MRF). Recall Eqn. (1) and Eqn. (2), the received amplitude at the Rx, which is co-located with the Tx, can be expressed as

$$A_d = A_0 g_t g_r \frac{\lambda}{4\pi(2d)} \cdot r \propto \frac{r}{d}. \quad (6)$$

The above expression accounts for the round-trip propagation distance  $2d$  and the reflection coefficient  $r$  of the target. Note that here  $d$  denotes the range of the target, i.e., the distance from the target surface to the radio. Let

$$A_d \triangleq \gamma \frac{1}{d},$$

then one can have

$$\gamma = A_0 g_t g_r \frac{\lambda}{8\pi} \cdot r = A_d \cdot d. \quad (7)$$

The defined  $\gamma$  has the following properties. First,  $\gamma$  is a linear function of the target reflection coefficient  $r$ , an

intrinsic characteristic of the target material, and is independent of the propagation distance. As shown by the middle term, except for three constants, i.e., the transmitting amplitude  $A_0$ , the Tx and Rx antenna gains  $g_t$  and  $g_r$ ,  $\gamma$  is only related to the reflection coefficient  $r$  and is thus unique to a particular material. Second, implied by the right term, one can easily estimate  $\gamma$  as long as one can obtain the range  $d$  of the target and the corresponding signal amplitude  $A_d$ .

As a result, one can term  $\gamma$  as the MRF and employ it for material identification, successfully avoiding the need of knowing the precise  $A_0$  to derive  $r$ . In practice, only an estimated version of  $\gamma$ , denoted as  $\hat{\gamma} = \hat{A}_d \hat{d}$ , can be obtained, where  $\hat{d}$  and  $\hat{A}_d$  are the estimated target range and the corresponding measured amplitude, respectively.

FIG. 16 illustrates an exemplary set of material reflection features (MRFs) of several common materials, according to some embodiments of the present disclosure. As shown in FIG. 16, preliminary measurements demonstrate that the MRF  $\gamma$  is discernible, reliable, and accurate in distinguishing different material types. The stronger the target reflects the incident signals, the larger MRF values it has. Albeit small variances exist, the measured MRFs of the exemplified materials are set apart as shown in FIG. 16.

A Channel Impulse Response (CIR) profiles the propagation delays and the channel responses of different signal paths between Tx and Rx, which is denoted by

$$h(\tau) = \sum_{l=1}^L a_l e^{-j\theta_l} \delta(\tau - \tau_l), \quad (8)$$

where  $a_l$ ,  $\theta_l$ , and  $\tau_l$  are the amplitude, phase and time delay of the  $l$ th path, respectively;  $L$  is the total number of paths and  $\delta(\tau)$  is the Dirac delta function. FIG. 17 shows an example of the CIR measured by an mmWave device. Each impulse tap of a CIR,  $h(\tau_l)$ , represents a delayed multipath component. The device uses a bandwidth of 3.52 GHz centered at 60 GHz frequency band, resulting in a time-of-flight (ToF) resolution of 0.28 nanosecond, which, given the speed of light  $c = 3 \times 10^8$  m/s, corresponds to a range resolution of 4.26 cm (for reflecting paths).

Compared to 2.4 GHz/5 GHz WiFi, the CIR of 60 GHz mmWave signals offer distinct advantages due to the many antennas, large bandwidth, and high carrier frequency. Applying the reported CIR for material sensing entails practical challenges. While the high range resolution is impressive for indoor localization, it is inadequate for material sensing. Furthermore, as demonstrated by experimental measurements, the device contains considerable noises and exhibits unreliable amplitudes, making the material sensing even challenging. Specifically, FIG. 17 shows the respective CIR measurements in the cases with and without a target in the field of interest. There are a few major challenges with the CIR estimation with the present implementation of the radar-like radio. First, the physical range resolution of 4.26 cm is inadequate for estimating the MRF precisely. Second, the reported CIR measurements over time might be out of synchronization. Third, there may be measurement noise. Ideally, the CIR should be all nearly zeros in absence of reflection objects. As shown in FIG. 17, the CIR measurements contain strong direct leakage from the Tx to the co-located Rx and noticeable internal reflection, significantly interfering the measurements in presence of a target.

Several operations are performed by the disclosed system to overcome the above mentioned challenges: CIR Interpolation, CIR Synchronization, and Noise Cancellation.

CIR Interpolation: To obtain finer details, one may up-sample the raw CIR via interpolation. Since the disclosed mSense system mainly utilizes CIR amplitudes for material identification, spline interpolation may be performed on the



amplitude, which subsamples the amplitude effectively. The interpolated CIR has denser sample points, and peak tap of a particular path tends to be close to the real maximum tap value. Thereby, the interpolation offers finer granularity in delay (and thus range) and amplitude estimation, both of which are critical to material identification. The mSense system may perform 8× interpolation, promoting the ToF precision to 35.2 picoseconds and promoting the distance precision to 0.52 cm. FIG. 18A illustrates an example with 2× and 16× interpolations of the original CIR. FIG. 18B illustrates the CIR amplitude after the noise cancellation, where the maximum CIR amplitude is after the first tap at the second tab.

CIR Synchronization: The default synchronization of the 60 GHz radio is not precise enough due to the resolution limit. For example, misalignment of one tap would lead to an offset of 4.26 cm in distance estimation. Neither is the synchronization reliable, i.e., the leakage tap would vary over time (especially due to temperature changes) and even over antenna pairs. To synchronize all the CIRs more precisely and reliably, one may leverage the direct leakage from the Tx to the Rx. The direct leakage between the co-located Tx and Rx is free of multipaths and produces a fixed time of flight, e.g. about 0.13 nanoseconds in a platform with a separation of about 4 cm between the Tx and the Rx. Thus, the direct leakage tap can serve as a reference tap, and the system may align this leakage tap of all CIR measurements to synchronize them and derive the relative ToF of each subsequent tap. The system can then obtain the absolute ToF for range estimation by compensating the ToF of the direct path from a specific Tx-Rx link on top of the relative ToF.

Regarding the synchronization, the system may first select one reference CIR whose direct leakage tap is assigned to a specific tap, denoted as the  $l_0$ th tap. Then for each CIR, the system may correlate it with the reference CIR. The correlation only involves the first  $L_0$  taps that cover the direct leakage, excluding the other taps that potentially associate with target or background reflections. Since the direct leakage keeps relatively stable with a similar pattern for different measurements, the tap at which the maximum correlation occurs is declared as the direct leakage tap. The CIR is accordingly synchronized by shifting the direct leakage tap to the  $l_0$ th tap, if they are different. To maintain the same length of the CIR, the system may perform circular shift for the alignment, which could alternatively be achieved by padding zeros to the first (or last) taps. The interpolated CIR may be used for the sake of finer-grained delays. The synchronization technique is also applicable to the general case of 60 GHz networking with unsynchronized, separate Tx and Rx devices. As long as the LOS distance between the Tx and Rx is known, all measurements can be synchronized by referring to the LOS delay, provided that the energy of LOS path dominates the other paths.

Noise Cancellation: The CIR can be modeled as a sum of the components reflected off the target, denoted as  $h^t$  and the components contributed by the direct leakage, internal reflection, measurement noises, and background reflection if any, denoted as  $h^n$ . To obtain  $h^t$  from the measured  $h$ , the system may utilize a reference CIR measured with no target

ing measurements when the device is pointing towards the air without the presence of the target. When there are  $Q$  such measurements,  $h^n$  will be estimated as the average sample, i.e.,

$$h^n(\tau_l) = \frac{1}{Q} \sum_{i=1}^Q h(\tau_l, t_i).$$

Then one may subtract  $h^n$  from a new  $h$  measured at time  $t$  towards a target and obtain  $h^t$ . Since the measured CIR amplitudes may slightly vary over time due to the automatic gain control (AGC), one may apply a scaling factor  $\beta$  for complete cancellation:

$$h^t(\tau, t) = h(\tau, t) - \beta h^n(\tau). \quad (9)$$

Assuming that the direct leakage should be constant, the scaling factor is computed based on the first  $L_0$  taps concerning only the direct leakage and noises by minimizing the mean square error (MMSE):

$$\beta^{\circ} = \operatorname{argmin}_{\beta} \sum_{l=1}^{L_0} |h(\tau_l, t) - \beta h^n(\tau_l)|^2. \quad (10)$$

In some embodiments, the cancellation is mainly used to remove the hardware distortions and measurement noises, rather than the background-tailored interferences. Therefore, the reference CIR can be a one-time calibration and does not need to be measured for every data capturing session, which largely consolidates its practical usage in mobile environments. In practice, it is possible to automatically collect the reference CIR since the system can detect whether there is a target within the range of interests (e.g., within 1 meter). If there is no target in the range of interest, the corresponding CIR samples can be used to generate the reference CIR. Although distant objects in the background (e.g., walls, furniture, etc.) may also reflect signals to be included in the reference CIR, they do not affect the wireless material sensing of the mSense system, because they are typically out of the range of interests.

Material Reflection Feature Estimation: Given that the direct leakage and internal reflection have been eliminated, one can simply locate the CIR tap that holds the maximum amplitude as the one where the target presents at and accordingly derive the relative ToF  $\Delta t$  corresponding to that tap. The associated amplitude is taken as the amplitude of the signals reflected by the target.

The ToF  $\Delta t$  derived from the synchronized CIR is the relative value referenced to the direct leakage tap. One can compensate the direct leakage delay to obtain the absolute ToF. Given the geometry of the Tx and Rx antenna arrays, the separation distance between each pair of Tx and Rx antennas can be pre-obtained, and the direct propagation delay can thereby be derived on top. For the  $M$  Tx antennas and  $N$  Rx antennas, an  $M \times N$  matrix  $S$  may be defined to represent the Tx-Rx separation distances, with  $s_{m,n}$  denoting its entry at the  $m$ th Tx element and the  $n$ th Rx element, where  $m=1, \dots, M, n=1, \dots, N$ . Then given the measurements between the  $m$ th Tx antenna and the  $n$ th Rx antenna, the range of the target can be computed by

$$d_{m,n} = \frac{c\Delta t_{m,n} + s_{m,n}}{2}. \quad (11)$$

Here half of the propagation distance is taken as the range, assuming normal incident, i.e., the device is pointing to the target approximately at elevation  $0^\circ$ .



The disclosed system can perform the above target detection for the CIR measured by every pair of Tx-Rx antennas and obtain  $M \times N$  estimates of  $\gamma$  in total, each denoted as

$$\gamma_{m,n} = \frac{A_{m,n} d_{m,n}}{g_t g_r}$$

for the  $m$ th Tx element and the  $n$ th Rx element, where  $A_{m,n}$  is the amplitude estimate at  $d_{m,n}$  and  $g_t, g_r$  are the AGC gains reported by the device. The system can leverage the antenna diversity to achieve a more robust estimate of  $\gamma$  by removing potential outliers in the target detection. Specifically, the system excludes those tuples whose distance estimate  $d_{m,n}$  deviates from the majority of all the  $M \times N$  estimates.

$$\hat{\gamma} = \frac{1}{|\mathcal{S}|} \sum_{(m,n) \in \mathcal{S}} \gamma_{m,n}. \quad (12)$$

Here  $\mathcal{S}$  is defined as the set of tuples  $(m, n)$  that satisfy  $\|d_{m,n} - \tilde{d}\| \leq \delta$ ,  $m=1, \dots, M$ ,  $n=1, \dots, N$ , where  $\delta$  is a threshold set to the default range resolution, i.e.,  $\delta=4.26$  cm,  $\tilde{d}$  is the median of all  $d_{m,n}$ .

The disclosed mSense system merely needs one single frame to yield an estimate of the MRF  $\gamma$ . In case there are multiple frames over time, the system will further improve the estimation by taking their average:

$$\bar{\gamma} = \frac{1}{K} \sum_{k=1}^K \hat{\gamma}(k), \quad (13)$$

where  $\hat{\gamma}(k)$  is the estimation from the  $k$ th CIR frame and  $K$  is total number of available frames. The device could be either moving or static during the measurements of successive frames.

Two steps are involved to identify material: an offline step to construct a database of the MRF for different materials; and an online step that retrieves the best matches for a given target.

Given a set of materials of interests, the system can perform a “scan” on each of them and store the distribution of the estimated  $\gamma$ . To reduce the data amount needed for training, one can build a histogram, rather than fitting a certain distribution, for each material type  $T$ , denoted as  $\{\langle \gamma_i(T), p_i(T) \rangle, i=1, 2, \dots, P\}$ , where  $\gamma_i(T)$  is the bin value and  $p_i(T)$  is the corresponding probability (normalized count of observations), and  $P$  is the total number of bins. In some embodiments, a median filter is applied to remove the outlier estimates from the training samples in prior to building the histogram. Let  $\mathcal{T}$  be the set of materials considered. Then in the online operating stage, for each material with  $\gamma$  to test, the best matching can be found as follows:

$$T^{\circ} = \underset{T \in \mathcal{T}}{\operatorname{argmin}} \sum_{i=1}^P \|\gamma - \gamma_i(T)\| \cdot p_i(T). \quad (14)$$

Besides, an additional rule can be applied to check the “null” class, i.e., the materials unseen in the training database. Specifically, for a given material, if its measured  $\gamma$  does

not match any  $\gamma_i(T)$ , for any  $i=1, \dots, P$  and any  $T \in \mathcal{T}$ , then the system treats it as the “unknown” type.

To present the overall recognition performance of the system, two frames per sample are used for training, while five frames are averaged as a testing sample. The impacts of the number of frames per sample will be evaluated subsequently. The results of both the mobile and static cases are fused together. As shown in FIG. 19A, the overall recognition accuracy is 92.87%, comparable to the existing works that need to penetrate the target with bilateral device setup and cannot be used for mobile material sensing. In some embodiments, the mSense system achieves a remarkable recognition accuracy exceeding 90% for all the tested materials except for ceramic, of which the estimated MRFs exhibit a larger variance and overlap with both plastic and water. In some embodiments, metals (e.g., aluminum) are identified correctly by the disclosed system with high accuracy, even in mobile cases, which would be particularly useful to detect suspicious targets for security. The accuracy promises valuable applications for ubiquitous contexts thanks to the mSense system’s simple setup of using single radio and reflection signals.

It is interesting to examine the performance of the mSense system in mobile environments. Thereby, as shown in FIGS. 19B and 19C, the accuracy of the wireless sensing of the system is demonstrated in mobile and static scenarios, respectively. As shown in FIGS. 19B and 19C, the overall performance in the static scenario is as expected slightly better than that in the mobile scenario, 93.66% v. 89.36%. The retained performance in mobile environments, with around 4% accuracy degradation, is delightful and sufficiently accurate for many everyday applications, considering that mmWave signals are sensitive to tiny location/orientation due to the short wavelength.

According to various embodiments of the present teaching, millimeter wave (mmWave, e.g. 28 GHz or 60 GHz) signals are used or re-used between a mmWave transmitter and a mmWave receiver to detect/recognize/differentiate a material of a target surface. The system exploits reflection characteristics (e.g. reflectivity) of the mmWave signal at the material surface, which are different from refraction characteristics of the mmWave signal through the material. As such, the transmitter and the receiver can be on the same side of the material, instead on two different sides of the material. The transmitter (transmitting device of the system with a processor/memory/software) and the receiver (receiving device of the system) may or may not be on a same device. The transmitter and/or receiver may each have an antenna array including distributed antennas. There may be multiple receivers each receiving the mmWave signal from the transmitter. There may be multiple transmitters each transmitting a respective mmWave signal to the receiver. There may be multiple transmitters and multiple receivers, where each transmitter transmits a respective mmWave signal to one or more receivers.

The device may have a commodity mmWave networking or communication chip/chipset which may operate in a radar mode enabled by attaching an extra antenna array to the chipset. It may use the chip/chipset to transmit the mmWave signal using a transmitting radio, and to receive the reflected mmWave signal using a receiving radio. The chip may transmit/receive simultaneously or contemporaneously. The chip may switch rapidly between transmitting and receiving to simulate or mimic “simultaneous” transmitting/receiving.

A user may hold the portable radio of the transmitter and/or receiver and point the antenna array towards the



target surface for a short instance (short time) in order for the system to capture the mmWave signal/CI needed for the material sensing.

In some embodiments, a transmitter transmits a mmWave signal onto a surface of unknown material. A receiver (e.g. on the same device as transmitter) receives the mmWave, extracts channel information (CI, such as signal strength/RSSI, channel state information/CSI, channel impulse response/CIR, and/or channel frequency response/CFR), analyzes the channel information to determine the material. It computes a material reflection feature (MRF) based on the CI that quantitatively characterizes the material's reflectivity, and detects or recognizes the material based on the MRF.

In a learning phase (or training stage), the system may capture training CI by shining mmWave signals onto a number of known material surface, extract the training CI, compute training MRF, apply machine learning to categorize/classify the training MRF, and compute reference MRF classes associated with the known materials. A database may be established based on the MRF classes and/or an associated classifier. In the learning phase, a histogram of MRF may be obtained for each known (training) material. The histogram may be cleaned (e.g. using median filter or lowpass filter) and normalized. An additional class of MRF called "null" may be added to account for any unknown material different from the known material.

In an operating (testing) phase, the system may capture testing CI by shining mmWave signals onto a test material surface, extract the testing CI, compute testing MRF, and analyze the testing MRF. The target material may be computed or determined as a known material associated with smallest conditional distortion (e.g. absolute distortion, square distortion, or a monotonic non-increasing function of absolute distortion).

The CI (or CSI or CIR or CFR) or MRF may be preprocessed/processed/postprocessed by (a) CI interpolation, (b) CI synchronization, (c) background/noise cancellation, (d) target detection, (e) MRF estimation, and/or (f) material identification. The CI (or CSI or CIR or CFR) or MRF may be preprocessed/processed by (1) interpolation to increase temporal resolution (with finer temporal details) of CI, (2) synchronization (e.g. direct path based), (3) background cancellation and/or noise cancellation to eliminate hardware distortion and measurement noise, (4) spatial diversity attributed by large antenna arrays to facilitate robustness, (5) estimating propagation distance associated with the target surface, (6) estimating the corresponding amplitude response, (7) computing the MRF, (8) associating the MRF with a particular reference MRF class, (9) determining the testing material as the material associated with the particular reference MRF class. One or more of the preprocessing/processing of CI may be applied in the learning phase and/or the operating phase.

The CI may be interpolated using linear interpolation, piecewise constant interpolation, polynomial interpolation, spline interpolation, fractional interpolation, extrapolation, and/or another interpolation. The interpolation may be performed in complex domain, real domain, imaginary domain, magnitude domain, and/or phase domain.

The transmitter and the receiver may be on the same device such that there may be direct leakage (line-of-sight/LOS transmission) between the transmitter and receiver leading to a very strong leakage pulse (e.g. observable in the CI, or CIR, or CFR) with a very strong local maximum of the magnitude (or magnitude square or any monotonic increasing function of magnitude) of CI.

In some embodiments, each pair of transmitting antenna and receiving antenna gives rise to a time series of CI (TSCI). Different TSCIs may not be synchronized and may exhibit different patterns due to different multipath propagation. The TSCIs may be synchronized by (i) searching for local/global maxima of each TSCI (or each time series of features of CI, the features being magnitude, magnitude square, time average, moving average, moving median, weighted average, autoregressive moving average (ARMA), correlation, a function of one or more of the previous, and/or other features) corresponding to the powerful direct leakage pulse and (ii) aligning the TSCI by aligning the associated local/global maxima.

Alternatively, one particular TSCI may be chosen as a reference TSCI, and a local maximum of the reference TSCI (or the associated features) corresponding to direct leakage may be identified. A time window of CI (i.e. a section of the reference TSCI) encompassing the high-energy direct leakage pulse shape (possibly including some past CI, but not future CI—to avoid including effects of multipaths from target surface) may be chosen as a reference window. The length of the time window may be associated with pulse width of the leakage pulse. Any other TSCI may be synchronized with respect to the reference TSCI by aligning the reference window to a corresponding time window of the other TSCI that gives maximum cross correlation or cross covariance.

By performing the CI interpolation before the CI synchronization, the synchronization may be performed in the higher sampling rate of the interpolated CI and thus at higher precision.

To perform background/noise (including direct leakage, internal reflection, measurement noise and background reflection) cancellation, the user may point the antenna array with no target in the field of interest (e.g. by removing the target and pointing the antenna array into air) and capture the CI for each pair of transmit antenna and receive antenna (which is effectively "background CI" which does not have effects of the target) associated with a respective TSCI. Multiple measurements may be taken and characteristic values (e.g. simple mean, weighted average, trimmed mean, median) may be taken as a robust estimate of the background CI. This process of obtaining background CI may be called "calibration" and may be performed once. The calibration may be a self-calibration as the system can detect if there is a target within the range of interest. Distant objects may not affect the material sensing as the distant objects are typically out of range of interests.

The background CI may be scaled and then subtracted from the respective TSCI. The scaling factor may be obtained by best-fitting (e.g. mean square error, mean absolute error, etc.) in a window encompassing the direct leakage profile (possibly including some past CI, but not future CI—to avoid including effects of multipaths from target surface). Alternatively, the background CI (for each link or each pair of transmit antenna and receive antenna) may be replaced by a common background CI obtained/computed for all pairs of transmit antennas and receive antennas.

In some embodiments, the distance of the target surface from the antenna array ("target distance") is needed to compute MRF. To find the distance, a search may be performed to find the tab with maximum CI amplitude (called "target reflection amplitude" which is amplitude of reflection at target material surface) in each background-subtracted TSCI for each respective transmit/receive antenna pair and the time-of-flight (ToF) may be obtained from the tab. The target distance may be computed based on



the ToF and a correction factor to account for distance between the transmit (Tx) antenna and the receive (Rx) antenna (or to account for the time of flight in LOS path between the Tx antenna and the Rx antenna, i.e. the time after the mmWave signal was transmitted and before it is received).

For each Tx/Rx antenna-pair, compute pair-wise MRF based on the target reflection amplitude, the target distance, Tx antenna gain (from Tx chip, the gain due to automatic gain control/AGC of Tx radio), and Rx antenna gain (from Rx chip, the gain due to AGC of Rx radio). The MRF may be computed as a product of the target reflection amplitude and the target distance divided by the Tx antenna gain and the Rx antenna gain.

A combined MRF may be computed as a representative value of the pair-wise MRF. A representative value may be mean, arithmetic mean, geometric mean, harmonic mean, weighted mean, trimmed mean, median, maximum likelihood (ML) value, maximum a posteriori (MAP) value, expected value/statistical mean, conditional mean, or another representative value.

The mmWave probe signal may be transmitted multiple times (each time being called a "frame"). Each frame may correspond to a different target distance as the user may move the antenna array and/or the target material surface may move or vibrate. In some embodiments, an aggregate MRF may be computed as a representative value of the combined MRF.

The following numbered clauses provide implementation examples for wireless material sensing.

Clause 1. A method/device/system/software of a wireless material sensing system, comprising: transmitting a wireless probe signal from a Type1 heterogeneous wireless device at a target material surface of an object using N1 transmit (Tx) antennas of the Type1 device through a wireless multipath channel of a venue, wherein the target material surface is a surface of a target material of the object; receiving the wireless probe signal by a Type2 heterogeneous wireless device using N2 receive (Rx) antennas of the Type2 device, wherein the received signal comprises at least one of: a reflection or a refraction, of the wireless probe signal at the target material surface; obtaining a plurality of channel information (CI) of the wireless multipath channel based on the received wireless probe signal using a processor, a memory communicatively coupled with the processor and a set of instructions stored in the memory, wherein each CI is associated with a Tx antenna of the Type1 device and a Rx antenna of the Type2 device, wherein each CI comprises at least one of: channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI); computing a material analytics based on the number of CI; and computing a type of the target material of the object based on the material analytics.

Clause 2. The method/device/system/software of the wireless material sensing system of clause 1, wherein: the material analytics is associated with the reflection of the wireless probe signal at the target material surface.

Clause 3. The method/device/system/software of the wireless material sensing system of clause 2, wherein: a CI associated with a Tx antenna and a Rx antenna comprises a CIR comprising of a number of tabs; the material analytics is based on at least one of: an amplitude of a tab of the CIR associated with the reflection of the wireless probe signal at the target material surface, a distance between the Tx antenna and the target material surface, a distance between the Rx antenna and the target material surface, a Tx gain

associated with the transmission of the wireless probe signal in the Type1 device, and an Rx gain associated with the reception of the wireless probe signal in the Type2 device.

Clause 4. The method/device/system/software of the wireless material sensing system of clause 2, wherein: each CI comprises a CIR with a number of tabs; the Tx antennas of the Type1 device and the Rx antennas of the Type2 device are in line-of-sight (LOS) such that the received signal comprises a direct LOS component of the wireless probe signal; each CIR has tabs with large magnitude corresponding to the LOS component of the wireless probe signal in the received signal.

Clause 5. The method/device/system/software of the wireless material sensing system of clause 4, wherein: the Type1 device and the Type2 device are the same device; the Tx antenna array and the Rx antenna array are next to each other.

Clause 6. The method/device/system/software of the wireless material sensing system of clause 5, wherein: the material analytics increases with: amplitude of tabs of CIRs associated with the reflection of the wireless probe signal at the target material surface, and the distance between the target material surface and the antenna arrays; and the material analytics decreases with: a Tx gain associated with the transmission of the wireless probe signal in the Type1 device, and an Rx gain associated with the reception of the wireless probe signal in the Type2 device.

Clause 7. The method/device/system/software of the wireless material sensing system of clause 6, wherein: the material analytics is proportional to a product of an amplitude of CIR tabs associated with the reflection and the distance between the target material surface and the antenna arrays; and the material analytics is inversely proportional to a product of the Tx gain and the Rx gain.

Clause 8. The method/device/system/software of the wireless material sensing system of clause 5, further comprising: interpolating all CIRs by an interpolation factor; and computing the material analytics based on the interpolated CIRs.

Clause 9. The method/device/system/software of the wireless material sensing system of clause 8, further comprising: synchronizing all the CIR; and computing the material analytics based on the synchronized CIRs.

Clause 10. The method/device/system/software of the wireless material sensing system of clause 9, further comprising: for each CIR: synchronizing a respective background CIR with the CIR, scaling the synchronized background CIR, and computing the respective background-subtracted CIR by subtracting the scaled synchronized background CIR from the CIR; and computing the material analytics based on the plurality of background-subtracted CIRs.

Clause 11. The method/device/system/software of the wireless material sensing system of clause 10, further comprising: computing a plurality of spatial-temporal quantities, each based on a respective background-subtracted CIR; computing the material analytics based on the plurality of spatial-temporal quantities.

Clause 12. The method/device/system/software of the wireless material sensing system of clause 8, further comprising: interpolating the CIRs based in at least one of: linear interpolation, polynomial interpolation and spline interpolation.

Clause 13. The method/device/system/software of the wireless material sensing system of clause 9, further comprising: aligning the CIRs based on LOS tabs, wherein the



LOS tabs are CIR tabs with large magnitude corresponding to the LOS component of the wireless probe signal.

Clause 14. The method/device/system/software of the wireless material sensing system of clause 13, further comprising: determining a particular CIR as a reference CIR; determining a reference window of tabs of the particular CIR encompassing its large-magnitude LOS tabs; computing matching score between the reference window of the reference CIR and a sliding window of another CIR in search of the best-matched sliding window with optimal matching score; aligning the another CIR with the reference CIR based on reference window and the best-matched sliding window; rotating the another CIR such that the best-matched sliding window is shifted to the same tab location as the reference window.

Clause 15. The method/device/system/software of the wireless material sensing system of clause 14, wherein: the tab location of the sliding window is within a search range of the tab location of the reference window; the matching score comprises at least one of: cross correlation, cross covariance,  $L_1$  distance, absolute difference,  $L_2$  distance, Euclidean distance,  $L_k$  distance, a function of the above, or another matching score.

Clause 16. The method/device/system/software of the wireless material sensing system of clause 13, further comprising: determining a particular CIR as a reference CIR; computing a representative tab location of the particular CIR; computing the representative tab location of a second CIR; aligning the second CIR with the reference CIR based on the representative tab locations of the reference CIR and the second CIR; rotating the second CIR such that its representative tab location is as close to the representative tab location of the reference CIR.

Clause 17. The method/device/system/software of the wireless material sensing system of clause 16, further comprising: computing the representative tab location of a CIR by normalizing the CIR and treating the normalized CIR as a probability density function (pdf) with its tab index being a real-valued variable  $X$  and the normalized CIR tab magnitude being its pdf  $f(X)$ ; wherein the representative tab location comprises at least one of: a mean of  $X$ , the expected value of  $X$ , the  $X$  corresponding to a centroid of  $f(X)$ , a mode of  $X$ , the value of  $X$  with maximum  $f(X)$ , a median of  $X$ , the value of  $X$  at 50-percentile, a 50-percentile of  $X$ , the value of  $X$  at  $Y$ -percentile wherein  $0 \leq Y \leq 100$ , a conditional mean of  $X$ , a conditional mode of  $X$ , a conditional median of  $X$ , a conditional percentile of  $X$ , a conditional quantity of  $X$  subject to at least one of:  $X$  is between the mean plus an offset  $Y_1$  and the mean plus an offset  $Y_2 \geq Y_1$ ,  $X$  is between the mode plus an offset  $Y_3$  and the mode plus an offset  $Y_4 \geq Y_3$ ,  $X$  is between the median plus an offset  $Y_5$  and the mode plus an offset  $Y_6 \geq Y_5$ , or  $X$  is between its  $Y_7$ -percentile and its  $Y_8$ -percentile, wherein  $0 \leq Y_7 \leq Y_8 \leq 100$ ; wherein the conditional quantity comprises at least one of: conditional mean, conditional mode, conditional median, or conditional  $Y$ -percentile.

Clause 18. The method/device/system/software of the wireless material sensing system of clause 10, further comprising: transmitting another wireless probe signal from the  $N_1$  Tx antennas of the Type1 device through the wireless multipath channel of the venue with the object removed in a field of interest; receiving the another wireless probe signal by the  $N_2$  Rx antennas of the Type2 heterogeneous wireless; obtaining the plurality of background CIRs of the wireless multipath channel based on the received another wireless probe signal, wherein the respective background CIR sub-

tracted from the respective CIR is associated with the same Tx and Rx antennas associated with the respective CIR.

Clause 19. The method/device/system/software of the wireless material sensing system of clause 18, further comprising: obtaining a plurality of trial CIRs of the wireless multipath channel based on the received another wireless probe signal; detecting if there is object or not in the field of interest based on the plurality of trial CIRs; if no object is detected, obtaining the plurality of background CIRs as the plurality of trial CIRs automatically; otherwise, repeating the procedures by transmitting and receiving yet another wireless probe signal to obtain another plurality of trial CIRs.

Clause 20. The method/device/system/software of the wireless material sensing system of clause 10, further comprising: scaling all tabs of the synchronized background CIR by a scaling factor; computing the scaling factor to optimize a matching score between the CIR and the scaled synchronized background CIR, wherein the matching score comprises at least one of: cross correlation, cross covariance,  $L_1$  distance, absolute difference,  $L_2$  distance, Euclidean distance,  $L_k$  distance, a function of the above, or another matching score.

Clause 21. The method/device/system/software of the wireless material sensing system of clause 10, further comprising: computing a plurality of candidate material analytics, each based on a respective background-subtracted CIR; computing the material analytics as an aggregate analytics of the plurality of candidate material analytics, wherein the aggregate analytics comprises at least one of: a mean, a mode, a median, a percentile, a scaling, a weighted mean, a trimmed mean, a geometric mean, a harmonic mean, or a function of any of the above.

Clause 22. The method/device/system/software of the wireless material sensing system of clause 21, further comprising: for each Tx antenna and for each Rx antenna: determining that a background-subtracted CIR is associated with the Tx antenna and the Rx antenna, with a first CIR tab associated with the LOS component of the wireless probe signal, identifying a maximum magnitude of the background-subtracted CIR after the first CIR tab, the maximum magnitude associated with a second CIR tab of the background-subtracted CIR, computing the candidate material analytics based on the second CIR tab and the maximum magnitude.

Clause 23. The method/device/system/software of the wireless material sensing system of clause 22, further comprising: for the Tx antenna and the Rx antenna: determining a first distance between the Tx antenna and the Rx antenna, computing a time difference between the first CIR tab and the second CIR tab, computing a second distance based on the time difference, computing a third distance based on the first distance and the second distance, and computing the associated candidate material analytics based on the maximum magnitude and the third distance.

Clause 24. The method/device/system/software of the wireless material sensing system of clause 23, wherein: the time difference is computed based on a sampling frequency of the CIR; the second distance is computed as a product of a wave propagation speed of the wireless probe signal in the venue and the time difference; the third distance is computed as a weighted sum of the first distance and the second distance; the associated candidate material analytics is computed based on at least one of: a transmitter gain, a receiver gain, and a sum of the first distance and the second distance.

Clause 25. The method/device/system/software of the wireless material sensing system of clause 1, further com-



prise: transmitting an additional wireless probe signal from the N1 Tx antennas of the Type1 device at the target material surface of the object through the wireless multipath channel of the venue; receiving the additional wireless probe signal by the N2 Rx antennas of the Type2 device; obtaining a plurality of additional CIs of the wireless multipath channel based on the received additional wireless probe signal, wherein each additional CI is associated with a Tx antenna of the Type1 device and a Rx antenna of the Type2 device, wherein each additional CI comprises at least one of: channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI); computing an additional material analytics based on the number of additional CI; and computing the type of the target material of the object based on the additional material analytics.

Clause 26. The method/device/system/software of the wireless material sensing system of clause 25, further comprise: computing an aggregate material analytics based on the material analytics and the additional material analytics; and computing the type of the target material of the object based on the aggregate material analytics.

Clause 27. The method/device/system/software of the wireless material sensing system of clause 25, further comprise: refining the material analytics based on the additional material analytics.

Clause 28. The method/device/system/software of the wireless material sensing system of clause 1, further comprise: in a training phase: for each of a plurality of training material: transmitting a wireless training probe signal from N3 Tx antennas of a training Type1 device at a training material surface of a respectively training object through a training wireless multipath channel of a training venue, receiving the wireless training probe signal by N4 Rx antennas of a training Type2 device, obtaining a plurality of training CIs of the training wireless multipath channel based on the received wireless training probe signal, wherein each training CI is associated with a Tx antenna of the training Type1 device and a Rx antenna of the training Type2 device, wherein each training CI comprises at least one of: channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI), and computing a training material analytics based on the number of additional CI, and training a classifier based on machine learning and the training material analytics of each training material; in an operating phase: computing the type of the target material of the object based on the classifier.

The features described above may be implemented advantageously in one or more computer programs that are executable on a programmable system including at least one programmable processor coupled to receive data and instructions from, and to transmit data and instructions to, a data storage system, at least one input device, and at least one output device. A computer program is a set of instructions that may be used, directly or indirectly, in a computer to perform a certain activity or bring about a certain result. A computer program may be written in any form of programming language (e.g., C, Java), including compiled or interpreted languages, and it may be deployed in any form, including as a stand-alone program or as a module, component, subroutine, a browser-based web application, or other unit suitable for use in a computing environment.

Suitable processors for the execution of a program of instructions include, e.g., both general and special purpose microprocessors, digital signal processors, and the sole processor or one of multiple processors or cores, of any kind of computer. Generally, a processor will receive instructions and data from a read-only memory or a random access

memory or both. The essential elements of a computer are a processor for executing instructions and one or more memories for storing instructions and data. Generally, a computer will also include, or be operatively coupled to communicate with, one or more mass storage devices for storing data files; such devices include magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; and optical disks. Storage devices suitable for tangibly embodying computer program instructions and data include all forms of non-volatile memory, including by way of example semiconductor memory devices, such as EPROM, EEPROM, and flash memory devices; magnetic disks such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM and DVD-ROM disks. The processor and the memory may be supplemented by, or incorporated in, ASICs (application-specific integrated circuits).

While the present teaching contains many specific implementation details, these should not be construed as limitations on the scope of the present teaching or of what may be claimed, but rather as descriptions of features specific to particular embodiments of the present teaching. Certain features that are described in this specification in the context of separate embodiments may also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment may also be implemented in multiple embodiments separately or in any suitable sub-combination.

Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments, and it should be understood that the described program components and systems may generally be integrated together in a single software product or packaged into multiple software products.

Particular embodiments of the subject matter have been described. Any combination of the features and architectures described above is intended to be within the scope of the following claims. Other embodiments are also within the scope of the following claims. In some cases, the actions recited in the claims may be performed in a different order and still achieve desirable results. In addition, the processes depicted in the accompanying figures do not necessarily require the particular order shown, or sequential order, to achieve desirable results. In certain implementations, multitasking and parallel processing may be advantageous.

We claim:

1. A system for wireless material sensing, comprising:
  - a transmitter configured for transmitting, using a plurality of transmit antennas, a first wireless signal through a wireless multipath channel of a venue;
  - a receiver configured for receiving, using a plurality of receive antennas, a second wireless signal through the wireless multipath channel, wherein the second wireless signal comprises a reflection or a refraction of the first wireless signal at a target material surface of an object in the venue, wherein the target material surface is a surface of a target material of the object; and
  - a processor configured for:
    - obtaining a plurality of channel information (CI) of the wireless multipath channel based on the second wireless signal, wherein each CI is associated with a



respective one of the plurality of transmit antennas of the transmitter and associated with a respective one of the plurality of receive antennas of the receiver, wherein each CI comprises at least one of: a channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI),  
 5 computing a material analytics based on the plurality of CI, wherein the material analytics is distinguishable for different candidate material types at the target material surface when the first wireless signal is reflected or refracted at the target material surface, and  
 10 determining, among the different candidate material types, a type of the target material of the object based on the material analytics.

**2.** The system of claim **1**, wherein:  
 the first wireless signal is a wireless probe signal; and  
 the material analytics is associated with the reflection of the wireless probe signal at the target material surface.

**3.** The system of claim **2**, wherein:  
 a CI associated with a transmit antenna and a receive antenna comprises a CIR including a number of tabs; and  
 the material analytics is computed based on at least one of:  
 25 an amplitude of a tab of the CIR associated with the reflection of the wireless probe signal at the target material surface,  
 a location of the tab of the CIR associated with the reflection of the wireless probe signal at the target material surface,  
 30 a distance between the transmit antenna and the target material surface,  
 a distance between the receive antenna and the target material surface,  
 35 a transmit antenna gain associated with transmitting the first wireless signal at the transmitter, or  
 a receive antenna gain associated with receiving the second wireless signal at the receiver.

**4.** The system of claim **2**, wherein:  
 each CI comprises a CIR with a number of tabs;  
 the plurality of transmit antennas of the transmitter and the plurality of receive antennas of the receiver are in line-of-sight (LOS) such that the second wireless signal  
 45 comprises a LOS component of the wireless probe signal; and  
 each CIR comprises a tab with a magnitude corresponding to the LOS component of the wireless probe signal.

**5.** The system of claim **4**, wherein:  
 the transmitter and the receiver are physically coupled to each other;  
 the plurality of transmit antennas and the plurality of receive antennas are next to each other;  
 the material analytics is proportional to a product of (a) an amplitude of CIR tabs associated with the reflection  
 55 and (b) a distance between the target material surface and the transmit and receive antennas; and  
 the material analytics is inversely proportional to a product of (c) a transmit antenna gain associated with transmitting the first wireless signal at the transmitter  
 60 and (d) a receive antenna gain associated with receiving the second wireless signal at the receiver.

**6.** The system of claim **5**, wherein the processor is further configured for:  
 interpolating all CIRs by an interpolation factor; and  
 65 computing the material analytics based on the interpolated CIRs.

**7.** The system of claim **6**, wherein the processor is further configured for:  
 synchronizing all of the interpolated CIRs; and  
 computing the material analytics based on the synchronized CIRs.

**8.** The system of claim **7**, wherein the processor is further configured for:  
 for each CIR:  
 synchronizing a respective background CIR with the CIR,  
 scaling the synchronized background CIR, and  
 computing a respective background-subtracted CIR by subtracting the scaled synchronized background CIR from the CIR; and  
 15 computing the material analytics based on the plurality of background-subtracted CIRs.

**9.** The system of claim **8**, wherein the processor is further configured for:  
 computing each of a plurality of spatial-temporal quantities based on a respective background-subtracted CIR; and  
 20 computing the material analytics based on the plurality of spatial-temporal quantities.

**10.** The system of claim **8**, wherein:  
 the transmitter is further configured for transmitting, using the plurality of transmit antennas, an additional wireless probe signal through the wireless multipath channel of the venue, with the object removed from a field of interest;  
 the receiver is further configured for receiving, using the plurality of receive antennas, the additional wireless probe signal through the wireless multipath channel; and  
 the processor is further configured for obtaining the plurality of background CIRs of the wireless multipath channel based on the additional wireless probe signal, wherein both a respective CIR and a respective background CIR subtracted from the respective CIR are associated with a same transmit antenna and a same receive antenna.

**11.** The system of claim **10**, wherein the processor is further configured for:  
 obtaining a plurality of trial CIRs of the wireless multipath channel based on the additional wireless probe signal;  
 45 determining whether there is any object in the field of interest based on the plurality of trial CIRs to generate a determination result;  
 when the determination result indicates that there is no object in the field of interest, obtaining the plurality of background CIRs based on the plurality of trial CIRs automatically; and  
 when the determination result indicates that there is an object in the field of interest, informing the transmitter to transmit another wireless probe signal to obtain another plurality of trial CIRs.

**12.** The system of claim **8**, wherein the processor is further configured for:  
 scaling all tabs of the synchronized background CIR by a scaling factor,  
 60 wherein the scaling factor is chosen to maximize a matching score between the CIR and the scaled synchronized background CIR,  
 wherein the matching score is computed based on at least one of: cross correlation, cross covariance, L<sub>1</sub> distance, absolute difference, L<sub>2</sub> distance, Euclidean distance, or L<sub>k</sub> distance.



13. The system of claim 8, wherein the processor is further configured for:

computing each of a plurality of candidate material analytics based on a respective background-subtracted CIR, wherein the material analytics is an aggregate analytics of the plurality of candidate material analytics.

14. The system of claim 13, wherein computing each candidate material analytics comprises:

for each transmit antenna and each receive antenna:

determining that a background-subtracted CIR is associated with the transmit antenna and the receive antenna, with a first CIR tab associated with the LOS component of the wireless probe signal,

identifying a maximum magnitude of the background-subtracted CIR after the first CIR tab, wherein the maximum magnitude is associated with a second CIR tab of the background-subtracted CIR, and

computing the candidate material analytics based on the second CIR tab and the maximum magnitude.

15. The system of claim 14, wherein computing each candidate material analytics further comprises:

for the transmit antenna and the receive antenna:

determining a first distance between the transmit antenna and the receive antenna,

computing a time difference between the first CIR tab and the second CIR tab, based on a sampling frequency of the background-subtracted CIR,

computing a second distance based on a product of the time difference and a wave propagation speed of the wireless probe signal in the venue,

computing a third distance based on a weighted sum of the first distance and the second distance, and

computing the candidate material analytics based on the maximum magnitude and the third distance.

16. The system of claim 6, wherein:

the CIRs are interpolated based on at least one of: linear interpolation, polynomial interpolation or spline interpolation.

17. The system of claim 6, wherein the processor is further configured for:

aligning the CIRs based on LOS tabs, wherein each of LOS tabs is a CIR tab with a magnitude corresponding to the LOS component of the wireless probe signal.

18. The system of claim 17, wherein the processor is further configured for:

determining one of the CIRs as a reference CIR;

determining a reference window of tabs of the reference CIR encompassing at least one LOS tab;

computing a matching score between the reference window of the reference CIR and a sliding window of an additional CIR to determine a best-matched sliding window with a maximum matching score, wherein:

a tab location of the sliding window is within a search range with respect to a tab location of the reference window,

the matching score is computed based on at least one of: cross correlation, cross covariance,  $L_1$  distance, absolute difference,  $L_2$  distance, Euclidean distance, or  $L_k$  distance;

aligning the additional CIR with the reference CIR based on the reference window and the best-matched sliding window; and

rotating the additional CIR such that the best-matched sliding window is shifted to the same tab location as the reference window.

19. The system of claim 17, wherein the processor is further configured for:

determining one of the CIRs as a reference CIR;

computing a representative tab location of the reference CIR;

computing a representative tab location of an additional CIR, wherein each representative tab location of a corresponding CIR is computed by:

normalizing the corresponding CIR; and

generating a probability density function based on: a tab index of the normalized CIR and a tab magnitude of the normalized CIR;

aligning the additional CIR with the reference CIR based on the representative tab locations of the reference CIR and the additional CIR; and

rotating the additional CIR such that its representative tab location is closer to the representative tab location of the reference CIR.

20. The system of claim 1, wherein:

the transmitter is further configured for transmitting, using the plurality of transmit antennas, a third wireless signal through the wireless multipath channel of the venue;

the receiver is further configured for receiving, using the plurality of receive antennas, a fourth wireless signal through the wireless multipath channel, wherein the fourth wireless signal comprises a reflection or a refraction of the third wireless signal at the target material surface of the object in the venue; and

the processor is further configured for:

obtaining a plurality of additional CI of the wireless multipath channel based on the fourth wireless signal, wherein each additional CI is associated with a respective one of the plurality of transmit antennas and associated with a respective one of the plurality of receive antennas, wherein each additional CI comprises at least one of: a channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI),

computing an additional material analytics based on the plurality of additional CI,

computing an aggregate material analytics based on the material analytics and the additional material analytics, and

determining the type of the target material of the object based on the aggregate material analytics.

21. The system of claim 1, wherein:

in a training phase of the system, for each of a plurality of training materials:

the transmitter is configured for transmitting, using the plurality of transmit antennas, a first wireless training signal through a training wireless multipath channel of a training venue,

the receiver is configured for receiving, using the plurality of receive antennas, a second wireless training signal through the training wireless multipath channel, wherein the second wireless training signal comprises a reflection or a refraction of the first wireless training signal at a surface of the training material in the training venue, and

the processor is configured for:

obtaining a plurality of training CI of the training wireless multipath channel based on the second wireless training signal, wherein each training CI is associated with a respective one of the plurality of transmit antennas and associated with a respective one of the plurality of receive antennas, wherein each training CI comprises at least one of: a channel state information (CSI), channel



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impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI), and  
 computing a training material analytics based on the plurality of training CI;  
 in the training phase of the system, training a classifier based on machine learning and the training material analytics of each training material; and  
 in an operating phase of the system, determining the type of the target material of the object based on the classifier.

22. A receiving wireless device for wireless material sensing, comprising:  
 a processor;  
 a memory communicatively coupled to the processor; and  
 a receiver communicatively coupled to the processor, wherein:  
 the receiving wireless device is associated with a transmitting wireless device that is configured for transmitting, using a plurality of transmit antennas, a first wireless signal through a wireless multipath channel of a venue,  
 the receiver is configured for receiving, using a plurality of receive antennas, a second wireless signal through the wireless multipath channel,  
 the second wireless signal comprises a reflection or a refraction of the first wireless signal at a target material surface of an object in the venue,  
 the target material surface is a surface of a target material of the object, and  
 the processor is configured for:  
 obtaining a plurality of channel information (CI) of the wireless multipath channel based on the second wireless signal, wherein each CI is associated with a respective one of the plurality of transmit antennas and associated with a respective one of the plurality of receive antennas,  
 computing a material analytics based on the plurality of CI, wherein the material analytics is distinguishable for different candidate material types at the target material surface when the first wireless signal is reflected or refracted at the target material surface, and  
 determining, among the different candidate material types, a type of the target material of the object based on the material analytics.

23. The receiving wireless device of claim 22, wherein:  
 the first wireless signal is a wireless probe signal;  
 the plurality of transmit antennas and the plurality of receive antennas are in line-of-sight (LOS) such that the second wireless signal comprises a LOS component of the wireless probe signal;  
 each CI comprises a channel impulse response (CIR) with a number of tabs;  
 each CIR comprises a tab with a magnitude corresponding to the LOS component of the wireless probe signal; and  
 the processor is further configured for:  
 interpolating all CIRs by an interpolation factor,  
 synchronizing all of the interpolated CIRs, and  
 computing the material analytics based on the synchronized CIRs.

24. The receiving wireless device of claim 23, wherein the processor is further configured for:  
 for each CIR:  
 synchronizing a respective background CIR with the CIR,  
 scaling the synchronized background CIR, and  
 computing a respective background-subtracted CIR by subtracting the scaled synchronized background CIR from the CIR; and

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computing the material analytics based on the plurality of background-subtracted CIRs.

25. The receiving wireless device of claim 24, wherein the processor is further configured for:  
 computing each of a plurality of spatial-temporal quantities based on a respective background-subtracted CIR; and  
 computing the material analytics based on the plurality of spatial-temporal quantities.

26. The receiving wireless device of claim 24, wherein the processor is further configured for:  
 computing each of a plurality of candidate material analytics based on a respective background-subtracted CIR, wherein the material analytics is an aggregate analytics of the plurality of candidate material analytics.

27. The receiving wireless device of claim 26, wherein computing each candidate material analytics comprises:  
 for each transmit antenna and each receive antenna:  
 determining that a background-subtracted CIR is associated with the transmit antenna and the receive antenna, with a first CIR tab associated with the LOS component of the wireless probe signal,  
 identifying a maximum magnitude of the background-subtracted CIR after the first CIR tab, wherein the maximum magnitude is associated with a second CIR tab of the background-subtracted CIR, and  
 computing the candidate material analytics based on the second CIR tab and the maximum magnitude.

28. The receiving wireless device of claim 27, wherein computing each candidate material analytics further comprises:  
 for the transmit antenna and the receive antenna:  
 determining a first distance between the transmit antenna and the receive antenna,  
 computing a time difference between the first CIR tab and the second CIR tab, based on a sampling frequency of the background-subtracted CIR,  
 computing a second distance based on a product of the time difference and a wave propagation speed of the wireless probe signal in the venue,  
 computing a third distance based on a weighted sum of the first distance and the second distance, and  
 computing the candidate material analytics based on the maximum magnitude and the third distance.

29. A method of a wireless material sensing system, comprising:  
 transmitting, using N1 transmit antennas of a transmitter, a first wireless signal through a wireless multipath channel of a venue;  
 receiving, using N2 receive antennas of a receiver, a second wireless signal through the wireless multipath channel, wherein the second wireless signal comprises a reflection or a refraction of the first wireless signal at a surface of a target material of an object in the venue, wherein N1 and N2 are positive integers;  
 obtaining a plurality of channel information (CI) of the wireless multipath channel based on the second wireless signal, wherein each CI is associated with a respective one of the N1 transmit antennas and associated with a respective one of the N2 receive antennas, wherein each CI comprises at least one of: a channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI);  
 computing a material analytics based on the plurality of CI, wherein the material analytics is distinguishable for



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different candidate material types at the surface when the first wireless signal is reflected or refracted at the surface; and  
determining, among the different candidate material types, a type of the target material of the object based on the material analytics. 5

**30.** The method of claim **29**, further comprising:  
in a training phase of the wireless material sensing system, for each of a plurality of training materials:  
transmitting, using N3 transmit antennas of a training transmitter, a first wireless training signal through a training wireless multipath channel of a training venue, 10  
receiving, using N4 receive antennas of a training receiver, a second wireless training signal through the training wireless multipath channel, wherein the second wireless training signal comprises a reflection or a refraction of the first wireless training signal at a surface of the training material in the training venue, wherein N3 and N4 are positive integers, 15

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obtaining a plurality of training CI of the training wireless multipath channel based on the second wireless training signal, wherein each training CI is associated with a respective one of the N3 transmit antennas and associated with a respective one of the N4 receive antennas, wherein each training CI comprises at least one of: a channel state information (CSI), channel impulse response (CIR), channel frequency response (CFR), or received signal strength index (RSSI), and  
computing a training material analytics based on the plurality of training CI;  
in the training phase of the wireless material sensing system, training a classifier based on machine learning and the training material analytics of each training material; and  
in an operating phase of the wireless material sensing system, determining the type of the target material of the object based on the classifier and the material analytics.

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